ADA

GEP 6.5LT ENGINE CETANE WINDOW EVALUATION FOR ATJ/JP-8 FUEL BLENDS

INTERIM REPORT
TFLRF No. 470

by
Douglas M. Yost
Edwin A. Frame

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Patsy Muzzell
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD24, Task 2.4)

UNCLASSIFIED: Distribution Statement A. Approved for public release

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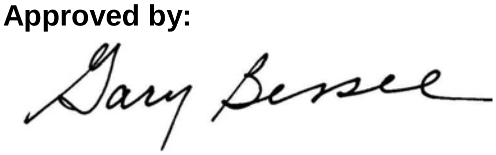

Gary B. Bessee, Director
U.S. Army TARDEC Fuels and Lubricants
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14. ABSTRACT

The European Stationary Cycle 13 Mode test and a power curve was performed on a 6.5L turbocharged V-8 diesel engine for three ATJ/JP-8 fuel blends. Full engine instrumentation was employed including in-cylinder pressure measurements. Engine operating parameters and exhaust gas emissions were recorded.

For the engine, clear trends for cetane-related performance were observed in the exhaust gas emissions, and potential cetane-related problems were identified at various conditions. Other fuel properties such as density, and bulk modulus also impacted engine performance.

15. SUBJECT TERMS
ATJ, Alcohol to Jet, Cetane Number, Synthetic Fuel, JP-8, diesel engine, combustion

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EXECUTIVE SUMMARY

A fuel's cetane number is very important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in diesel engine-powered ground vehicles and is studying the use of alternative jet fuels obtained from a variety of sources. Currently there is no cetane number specification for jet fuels as this property holds no significance for turbine engine operation. Therefore, it is of interest to identify a window, or range, of cetane number which would be acceptable to ensure the reliable operation of diesel engine-powered military ground vehicles.

A GEP 6.5LT engine was operated on three ATJ/JP-8 blends and evaluated for power, performance, and emissions over the 13-modes European Stationary Cycle and a full-load power curve. Full engine instrumentation was employed including in-cylinder pressure measurements. Engine operating parameters and exhaust gas emissions were recorded.

The three ATJ/JP-8 blends included 15%, 35% and 50% ATJ content with 44.2, 36.4 and 32.0 cetane numbers respectively. There was very little impact on power and performance with the ATJ fuel blends. Engine exhaust HC and CO emissions increased with increasing ATJ content in the blends. The engine Filter Smoke Number decreased with increasing ATJ content in the blends. The engine out NOx emissions were highest with the ATJ35 blend and lowest with the ATJ50 blend.

The combustion and fuel data from this testing was included into a data set from prior cetane window testing for the GEP 6.5LT engine [1]. The results from the ATJ testing data did not significantly alter the fuel property and performances correlations determined in a prior U.S. Army engine study.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period July 2013 through September 2015 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler served as the TARDEC contracting officer's technical representative. Ms. Patsy Muzzell of TARDEC served as project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by the TFLRF administrative staff.

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ACRONYMS AND ABBREVIATIONS

2-EHN	2-Ethylhexyl Nitrate
50MFB	50-Percent Mass Fraction Burned
ATDC	After Top Dead Center
ATJ	Alcohol-to-Jet Alternative Fuel
BM	Bulk Modulus
BMEP	Brake Mean Effective Pressure
BSCO	Brake Specific Carbon Monoxide
BSFC	Brake Specific Fuel Consumption
BSHC	Brake Specific Hydrocarbons
$BSNO_x$	Brake Specific Oxides of Nitrogen
CA50	Crank Angle 50 Timing (or the crank angle at which the 50% MFB occurs)
CAD	Crank Angle Degrees
CN	Cetane Number
CO	Carbon Monoxide
DAQ	Data Acquisition
DCN	Derived Cetane Number
ESC	European Stationary Cycle
FSN	Filter Smoke Number
FTDSA	Fischer Tropsch Diesel from South Africa
FTDSH	Fischer Tropsch Diesel from Shell
GEP	General Engine Products
H/C	Hydrogen Atom to Carbon Atom Ratio
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
HRJ8	Hydro Treated Renewable Jet Fuel Number 8
HRR	Heat Release Rate
IPK	Iso Parrafinic Kerosene
IVC	Intake Valve Close
J/CAD	Joules per Crank Angle Degree
JP-8	Jet Propulsion Fuel Number 8
KVis	Kinematic Viscosity
LPP	Location of Peak Pressure
MFB	Mass Fraction Burned
MHRR	Maximum Heat Release Rate
MJ/L	Mega Joules per Liter
NHofC	Net Heat of Combustion
NOx	Oxides of Nitrogen (consisting of NO and NO2)
PLN	Pump Line Nozzle
PQIS	Petroleum Quality Information System
RPM	Revolutions per Minute
SOC	Start of Combustion
SOI	Start of Injection
SPK	Synthetic Paraffinic Kerosine
TDC	Top Dead Center

1.0 HISTORICAL BACKGROUND

A fuel's cetane number is critically important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in its ground vehicles. The U.S. military is currently studying the use of alternative jet fuels obtained from a variety of sources. Unfortunately there is no cetane number specification for jet fuels as this property holds no significance for turbine engine operation. As an example, data in the Petroleum Quality Information System (PQIS) database and from SwRI's own fuel inventory have been used to graph the large variety in cetane index, (and for the alternative fuels, cetane number) versus energy density in currently available jet-type fuels, including the tested ATJ/JP-8 blends (Figure 1).

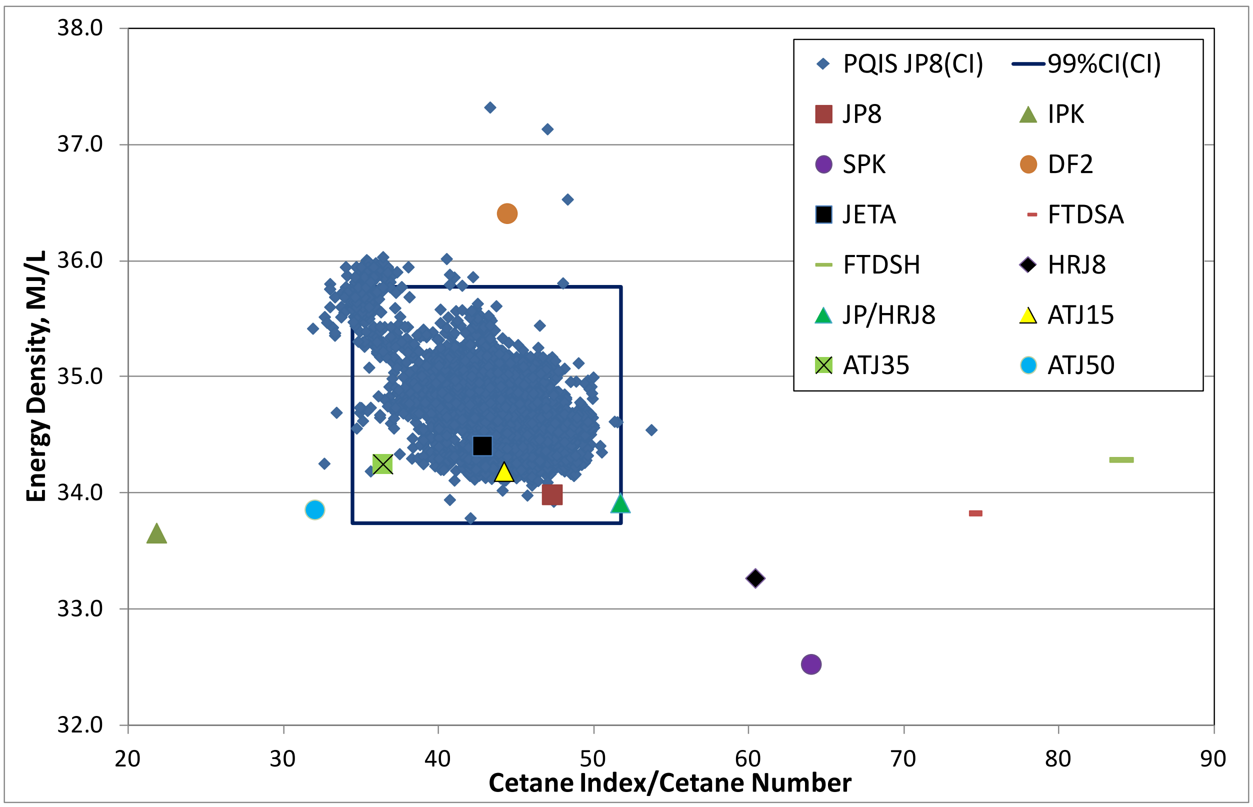


Figure 1. Historical Energy Density of JP-8 and Various Alternative Fuels vs. Cetane Index/Cetane Number

2.0 INTRODUCTION

The synthetic aviation kerosene fuel described as Alcohol-To-Jet (ATJ) has a very low cetane number in its neat form. The cetane number of ATJ fuel is sufficiently low that a 50/50 blend with petroleum JP-8 would be below the Army requirement for 40 cetane minimum for use with diesel engines. For the GEP 6.5LT engine studied in this program, the goal was to observe cetane-related performance trends of three ATJ blends and specifically measure power, combustion characteristics, and exhaust gas emissions. It was also important to identify potential cetane-related issues. Other fuel properties were measured such as density, and bulk modulus to determine their specific impacts on engine performance.

3.0 EQUIPMENT

The engine used for this program was a General Engine Products (GEP) 6.5LT (V-8, turbocharged, indirect injected diesel engine).

3.1 MAINTENANCE

Prior to testing, the GEP 6.5LT engine was verified for proper operation. The engine utilized was the same engine used for prior combustion work and cold start testing, and has had less than 100-hours operation on its build. In addition a new fuel injection pump and fuel injectors were also installed on the engine. Steps were taken to insure the fuel injection timing was correct for the engine after installation of the new fuel injection system. Total test time for ATJ blend testing on the engine was less than 50 hours, so no maintenance items were performed during the testing period.

4.0 OPERATING CONDITIONS

For each test fuel blend the GEP 6.5LT engine was operated over the 13-Mode European Stationary Cycle (ESC) along with additional points to fill out a full-load power curve. Three

points for the full-load power curve come from the ESC, with additional full-load points added at 1,000, 1,500, and 3,400-RPM engine speeds. The engine speed for rated power is 3,400-RPM.

4.1 EUROPEAN STATIONARY CYCLE LOAD STEPS

Each of the 13 modes of the ESC (see Figure 2) are governed by a mathematical formula, as explained below, for calculating the engine speeds A, B, & C. Each operating point also has a weighting value assigned to it for calculating the cycle average emissions.

GEP 6.5LT Engine Speeds
A = 1928 RPM
B = 2641 RPM
C = 2995 RPM

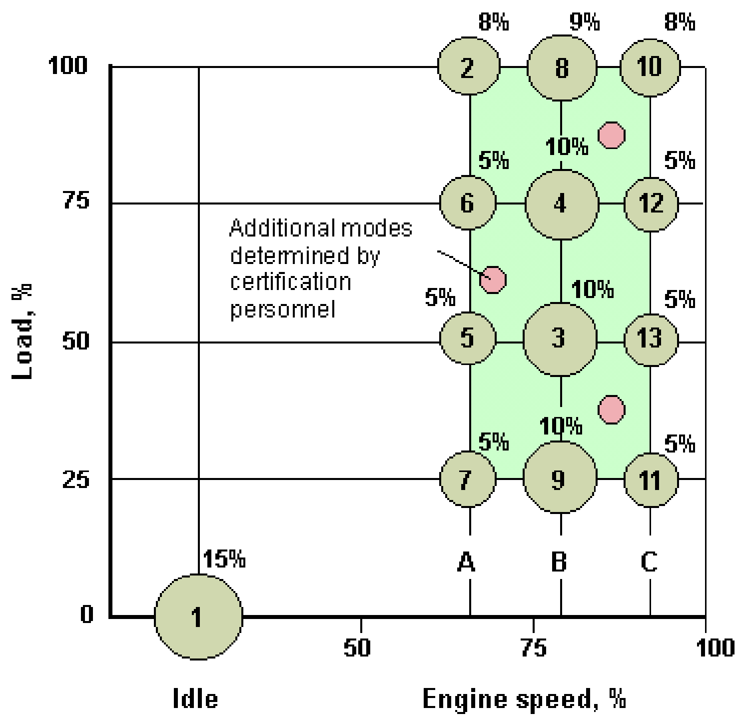


Figure 2. ESC 13 Mode Cycle Description

The engine speeds are defined as follows:

1. The high speed n_{hi} is determined by calculating 70% of the declared maximum net power. The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as n_{hi}.

2. The low speed n_{lo} is determined by calculating 50% of the declared maximum net power. The lowest engine speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as n_{lo}.

3. The engine speeds A, B, and C to be used during the test are then calculated from the following formulas:

   $A = n_{lo} + 0.25(n_{hi} - n_{lo})$; $B = n_{lo} + 0.50(n_{hi} - n_{lo})$; $C = n_{lo} + 0.75(n_{hi} - n_{lo})$

4.2 CONTROLS

On the GEP 6.5LT engine, the coolant, oil, inlet air, and fuel temperatures were all closed loop controlled. The engine operating points for each ESC mode can be seen below in Table 1, along with additional points included to fill out the full-load power curve.

Table 1. GEP 6.5LT ESC Engine Operating Conditions

ESC MODE	Speed RPM	Load lb-ft	Coolant Outlet °F	Oil Sump °F	Inlet Air °F	Fuel Inlet °F
ESC1	800	7.5	190	200	75	95
ESC2	1928	335		220		
ESC3	2641	161				
ESC4	2641	242				
ESC5	1928	170				
ESC6	1928	256				
ESC7	1928	85				
ESC8	2641	306				
ESC9	2641	81				
ESC10	2995	288				
ESC11	2995	71				
ESC12	2995	217				
ESC13	2995	144				
POWER CURVE	Speed RPM	Load %	Coolant Outlet °F	Oil Sump °F	Inlet Air °F	Fuel Inlet °F
Rated	3400	100%	190	220	75	95
ESC10	2995	100%				
ESC8	2641	100%				
ESC2	1928	100%				
1500FL	1500	100%				
1000FL	1000	100%				

5.0 INSTRUMENTATION

Full engine instrumentation was employed including in-cylinder pressure. All relevant engine operating temperatures, pressures and exhaust gas emissions were recorded.

5.1 ENGINE SETUP

The high speed instrumentation for the GEP 6.5LT consisted of the following:

- 2x Kistler Cylinder Pressure Transducer, 6056A (Pre-Chamber) & 6052B (Main-Chamber)
- Kistler 5011 & 5018 Charge Amplifiers
- Kistler Fuel Line Pressure Transducer, 4065A1000 with matching pre-calibrated amplifier
- BEI Shaft Encoder (0.2 CAD)
- Wolff Instrumented Injector for needle lift

The high speed data was recorded and post-processed by a SwRI High Speed DAQ. A SwRI PRISM DAQ system was used for engine control and data recording of the slow speed instrumentation. A Horiba MEXA 1600D emissions bench was also used, Figure 3). An AVL-415 smoke meter was used to determine the Filter Smoke Number (FSN) at each operating condition.

During the initial test phases the line pressure transducer signal exhibited intermittent characteristics. The results for the injection line pressure were unreliable, so the line pressure data is not included in this study.

Figure 3. Horiba MEXA 1600D Emissions Bench

5.2 HIGH SPEED PRESSURE TRANSDUCERS - GEP 6.5LT

The Number 2 cylinder was instrumented for pressure on the GEP 6.5LT engine. This was done because it was both closest to the front of the engine where the shaft encoder was mounted and because the high pressure fuel line (coming out of the injection pump) was more accessible than the Number 1 cylinder line. Figure 4 shows the location of the fuel line pressure transducer. It is located at the outlet of the injection pump.

Figure 4. Injection Line Pressure Transducer (GEP 6.5LT)

Figure 5 shows the location in the head of the pre-chamber pressure transducer (which uses the glow plug port), the main chamber pressure transducer, and the instrumented injector.

Figure 5. GEP 6.5LT Cylinder Pressure Transducers and Instrumented Injector

Figure 6 is a sectioned view of the head for the GEP 6.5LT engine and shows the location of the main chamber pressure transducer in relation to the intake valve port and the pre-chamber port.

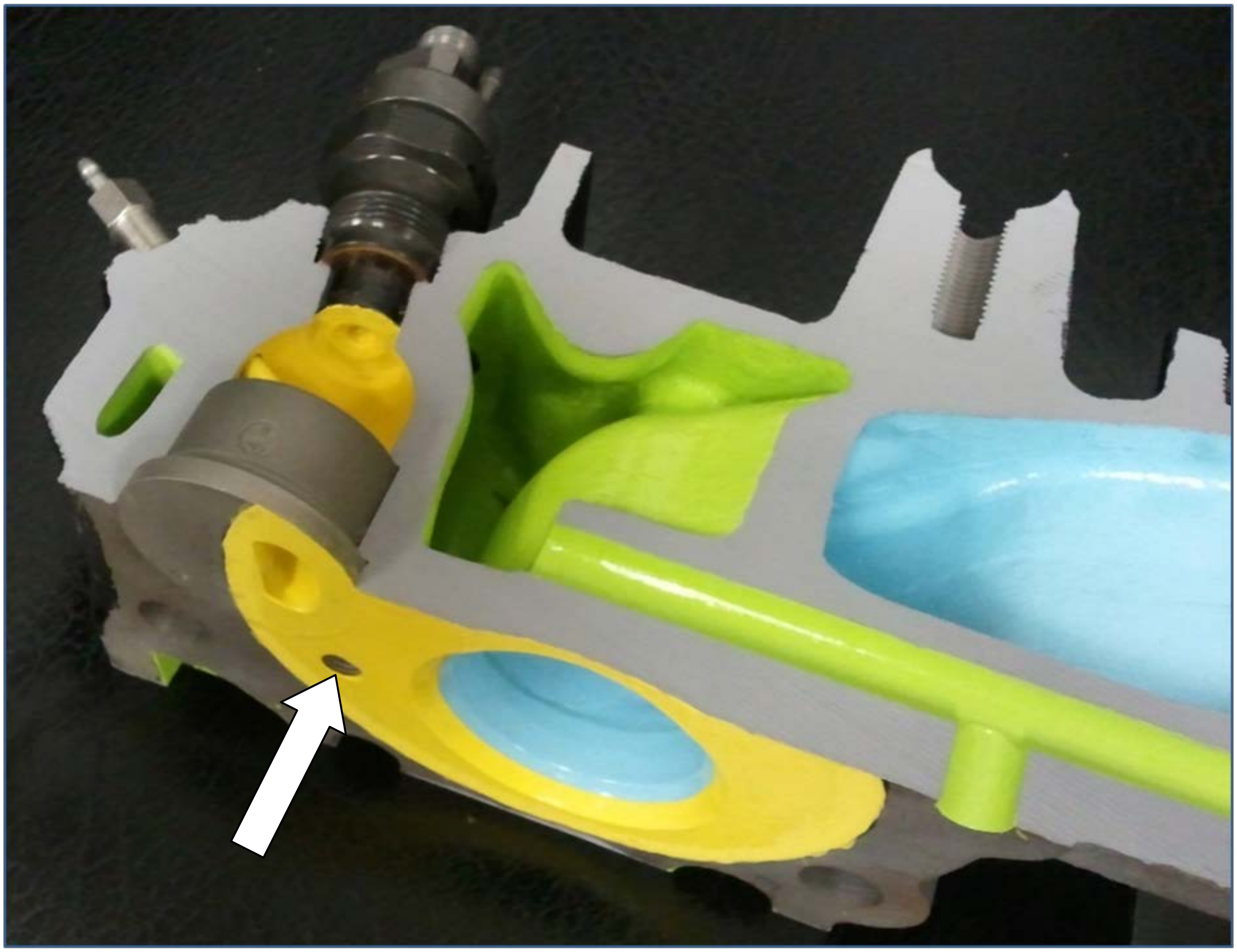


Figure 6. GEP 6.5LT Head Cut Away with Main Chamber Pressure Transducer Location Indicated

5.3 INSTRUMENTED INJECTORS – GEP 6.5LT

During testing with the GEP 6.5LT engine, it was observed that the injector, at almost every operating condition, opened more than once. This was found to be the direct result of a reflected pressure wave in the fuel line. The secondary injector opening was at a lower needle lift and a shortened duration. This is most likely the result of two items. The first is the pulse width of the pressure wave between 1,600 and 1,700 psi, which is the opening pressure range for the injector. The second is after the initial injection event, there is not any bulk fluid motion in the high pressure line due to the regular increment of the pump to the next cylinder. The impacts of this late injection opening would be a decrease in the cycle thermal efficiency and an increase in emissions, particularly Carbon Monoxide (CO) and Hydrocarbon (HC).

6.0 FUEL PROPERTIES

Included in this report is a selection of fuel properties for the three fuels used in the program. The fuel properties for the blends were determined in Task 2.1 of Work Directive 24 of the contract. The fuel properties in Table 2 are compared to the MIL-DTL-83133H fuel specification. The Bulk Modulus data for the three test fuel blends are included in Table 3.

The fuel property data from the three ATJ blends, along with the engine combustion and performance data, were combined with prior data for fifteen fuels reported in Interim Report No. 436, “Tactical/Combat Engine Cetane Window Evaluations,” [1] for trend analysis.

Table 2. ATJ/JP-8 Fuel Blend Property Data

Test	Method	Units	Sample ID CL14-6111 Results	Sample ID CL13-5982 Results	Sample ID CL13-5983 Results	MIL-DTL-83133H (Table I and A-II)
			15% ATJ	35% ATJ	50% ATJ	
Water Reaction	**D1094**					
Volume change of aqueous layer		**mL**	0.0	0.5	0.0	
Interface condition		**rating**	1b	1b	1b	1b max
Separation		**-**	2	2	2	
Copper Strip Corrosion (100°C, 2 hrs)	**D130**	**rating**	1A	1A	1A	1 max
Smoke Point	**D1322**	**mm**	26.0	28.0	29.5	25.0 min
Saybolt Color	**D156**	**-**	27	29	28	report
Freeze Point (manual)	**D2386**	**°C**	-55.0	-60.0	-62.0	-47 max
Electrical Conductivity vs. Temperature	**D2624**					
Temperature		**°C**	22.2	21.6	21.6	
Electrical Conductivity		**pS/m**	660	1230	890	150-600
JFTOT	**D3241**					
Test Temperature		**°C**	260	260	260	
ASTM Code		**rating**	1	1	1	<3
Maximum mmHg		**mmHg**	0	0	0	25 max
Acid Number	**D3242**	**mg KOH/g**	0.010	0.010	0.008	0.015 max
Existent Gum	**D381**	**mg/100mL**	1	1	<1	7 max
Density	**D4052**					
15 °C		**g/ml**	0.7896	0.7820	0.7766	0.775-0.840
Density	**D4052C**					
5 °C		**g/ml**	0.7969	0.7892	0.7838	
15 °C		**g/ml**	0.7896	0.7820	0.7766	0.775-0.840
25 °C		**g/ml**	0.7822	0.7746	0.7694	
35 °C		**g/ml**	0.7749	0.7674	0.7621	

Table 2. ATJ/JP-8 Fuel Blend Property Data

Test	Method	Units	Sample ID CL14-6111 Results	Sample ID CL13-5982 Results	Sample ID CL13-5983 Results	MIL-DTL-83133H (Table I and A-II)
			15% ATJ	35% ATJ	50% ATJ	
45 °C		g/ml	0.7675	0.7600	0.7548	
55 °C		g/ml	0.7601	0.7526	0.7475	
65 °C		g/ml	0.7527	0.7452	0.7401	
75 °C		g/ml	0.7452	0.7378	0.7327	
85 °C		g/ml	0.7376	0.7303	0.7252	
Kinematic Viscosity	D445					
100 °C		cSt	0.70	0.70	0.71	
40 °C		cSt	1.33	1.35	1.37	
-20 °C		cSt	4.48	4.49	4.53	8.0 max
Lubricity (BOCLE)	D5001	mm	0.650	0.700	0.700	
Lubricity (HFRR) at 60 °C	D6079	µm	731	704	653	
Fuel System Icing Inhibitor (FSII) Content at 22 °C	D5006	vol %	0.08 (24°C)	0.09	0.09	0.07-0.10
Particulate Contamination in Aviation Fuels	D5452					
Total Contamination		mg/L	0.3	0.2	0.2	1.0 max
Total Volume Used		mL	1000	1000	1000	
Distillation	D86					
IBP		°C	172.9	172.6	173.1	
5%		°C	182.5	181.0	179.5	
10%		°C	184.7	181.8	180.7	205 max
15%		°C	187.0	182.6	181.7	
20%		°C	188.5	184.8	182.6	
30%		°C	193.5	188.3	185.9	
40%		°C	198.0	192.2	188.6	
50%		°C	202.6	196.1	192.4	
60%		°C	208.0	201.5	196.6	

Table 2. ATJ/JP-8 Fuel Blend Property Data

Test	Method	Units	Sample ID CL14-6111 Results 15% ATJ	Sample ID CL13-5982 Results 35% ATJ	Sample ID CL13-5983 Results 50% ATJ	MIL-DTL-83133H (Table I and A-II)
70%		°C	214.9	208.4	203.6	
80%		°C	223.2	219.2	214.9	
90%		°C	234.8	232.5	231.4	
95%		°C	245.2	242.1	241.4	
FBP		°C	255.0	254.5	256.1	300 max
Residue		%	1.3	1.4	1.3	1.5 max
Loss		%	1.1	0.3	0.3	1.5 max
T50-T10		°C	17.9	14.3	11.7	15 min
T90-T10		°C	50.1	50.7	50.7	40 min
Flash Point (Pensky Martin)	D93	°C	56.5	49.5	49.5	38 min
Cetane Index	D976	-	49.9	50.3	51.0	
Particle Count by APC (Cumulative)	ISO-4406					
>= 4µm(c)		class code	16	16	17	
>= 6µm(c)		class code	15	15	16	
>= 14µm(c)		class code	11	12	12	
>= 21µm(c)		class code	10	11	11	
>= 38µm(c)		class code	7	7	7	
>= 70µm(c)		class code	0	0	0	
Heat of Combustion - Net Intermediate	D4809	MJ/kg	43.3	43.8	43.6	42.8 min
Sulfur-Mercaptan	D3227	mass %	0.0004	<0.0003	<0.0003	0.002 max
Derived Cetane Number	D6890					
Ignition Delay, ID		ms	4.586	5.103	5.728	
Derived Cetane Number		---	45.15	41.02	37.04	40 min
Cetane Number	D613	-	44.2	36.4	32.0	
MSEP	D7224	rating	60	67	72	70 min

Table 2. ATJ/JP-8 Fuel Blend Property Data

Test	Method	Units	Sample ID CL14-6111 Results	Sample ID CL13-5982 Results	Sample ID CL13-5983 Results	MIL-DTL-83133H (Table I and A-II)
			15% ATJ	35% ATJ	50% ATJ	
Aromatic Content	**D1319**					
Aromatics		**vol %**	15.0	11.1	8.5	8.0-25.0
Olefins		**vol %**	1.6	2.9	2.0	
Saturates		**vol %**	83.4	86.0	89.5	
Naphthalene Content	**D1840**	**vol%**	0.66	0.50	0.40	3.0 max
Hydrogen Content (NMR)	**D3701**	**mass %**	14.26	14.63	14.85	13.4 min
Sulfur Content	**D4294**	**ppm**	844	650	506	3000 max

Table 3. ATJ/JP-8 Fuel Blend Bulk Modulus Data

Sample ID CL14-6111 Results			Sample ID CL13-5982 Results			Sample ID CL13-5983 Results		
15% ATJ			35% ATJ			50% ATJ		
Pressure (psi)	Speed-of-Sound (m/s)	Bulk Modulus (psi)	Pressure (psi)	Speed-of-Sound (m/s)	Bulk Modulus (psi)	Pressure (psi)	Speed-of-Sound (m/s)	Bulk Modulus (psi)
35°C								
184	1247.4	174,382	184	1231.4	168,272	222	1223.6	165,157
718	1270.3	181,466	832	1260.1	177,035	832	1246.7	172,176
1519	1307.9	193,344	1633	1292.7	187,320	1900	1291.8	186,184
2091	1324.3	198,919	2320	1317.6	195,412	2816	1323.5	196,538
3007	1358.3	210,430	3770	1373.5	214,167	3732	1364.7	210,057
4075	1393.4	222,741	4761	1405.5	225,450	4723	1394.8	220,659
4838	1418.2	231,613	5601	1426.1	233,109	5868	1425.4	231,864
5715	1445.5	241,702						
75°C								
336	1102.2	131,146	222	1089.5	126,764	184	1069.3	121,184
603	1116.8	134,958	1557	1150.8	143,138	832	1102.4	129,701
1328	1151.5	144,409	2358	1187.3	153,334	1519	1133.8	137,967
2091	1184.1	153,580	3045	1218.5	162,304	2167	1168.1	147,208
2740	1216.0	162,764	3655	1235.2	167,543	2892	1194.8	154,901
3388	1242.3	170,648	4761	1282.9	182,045	3884	1234.5	166,530
4647	1283.4	183,555	5334	1305.1	189,079	4990	1282.9	181,160
5448	1311.4	192,552				5944	1312.1	190,696

7.0 TEST RESULTS

7.1 FULL-LOAD POWER CURVE

Performance data from the full-load power curves for each ATJ/JP-8 blend are included in Table 4 and are plotted in Figure 7 through Figure 9. The ATJ15 fuel, which has the highest cetane number of the three ATJ blends due to the greater JP-8 content, shows a slightly greater peak engine torque at 1,928-RPM versus the other blends as seen in Figure 7. All other torques across the speed range was very similar for the blends in the GEP 6.5LT engine.

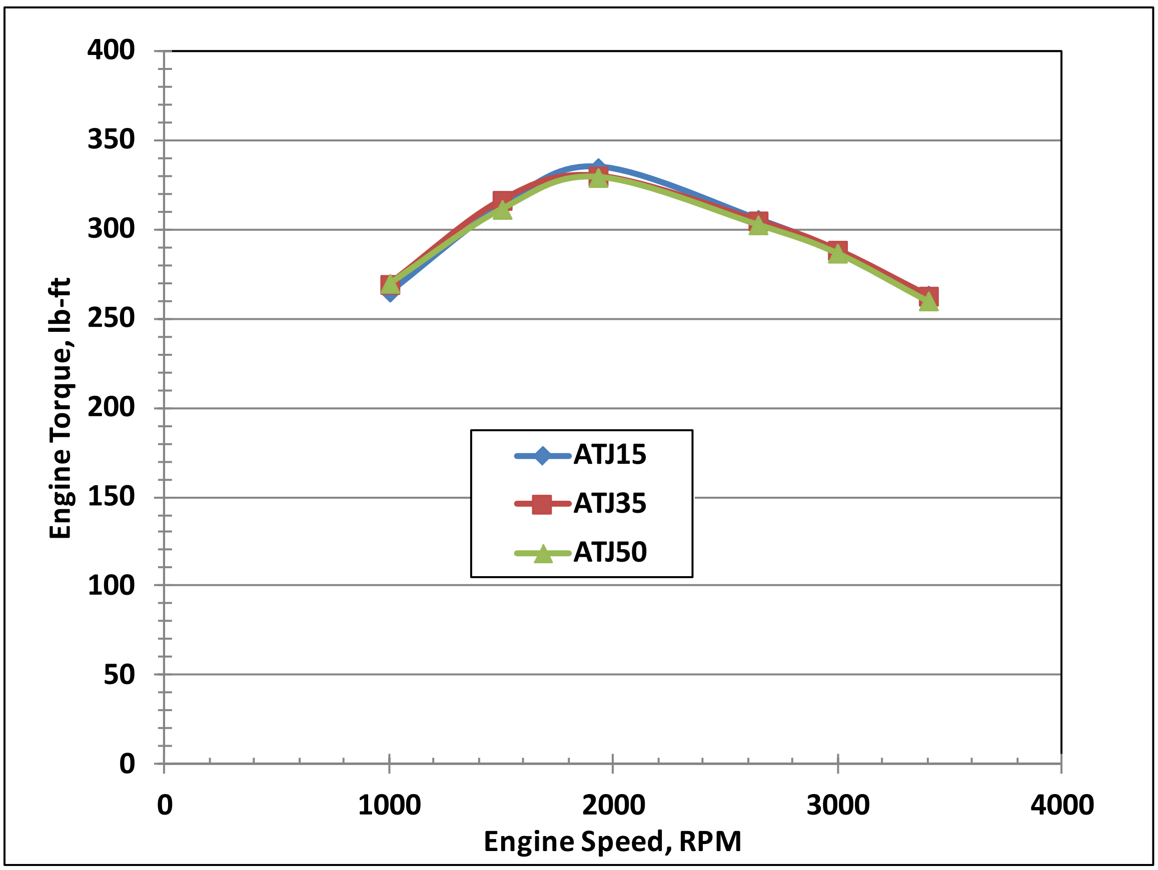


Figure 7. GEP 6.5LT Full Load Brake Torque for ATJ/JP-8 Test Fuels

Shown in Figure 8, the ATJ50 fuel, which has the lowest cetane number of the three ATJ blends, due to the greater ATJ content, shows a slightly lower peak engine brake horsepower at the 3,400-RPM rated engine speed versus the other blends. All other power levels across the speed range were very similar for the blends in the GEP 6.5LT engine.

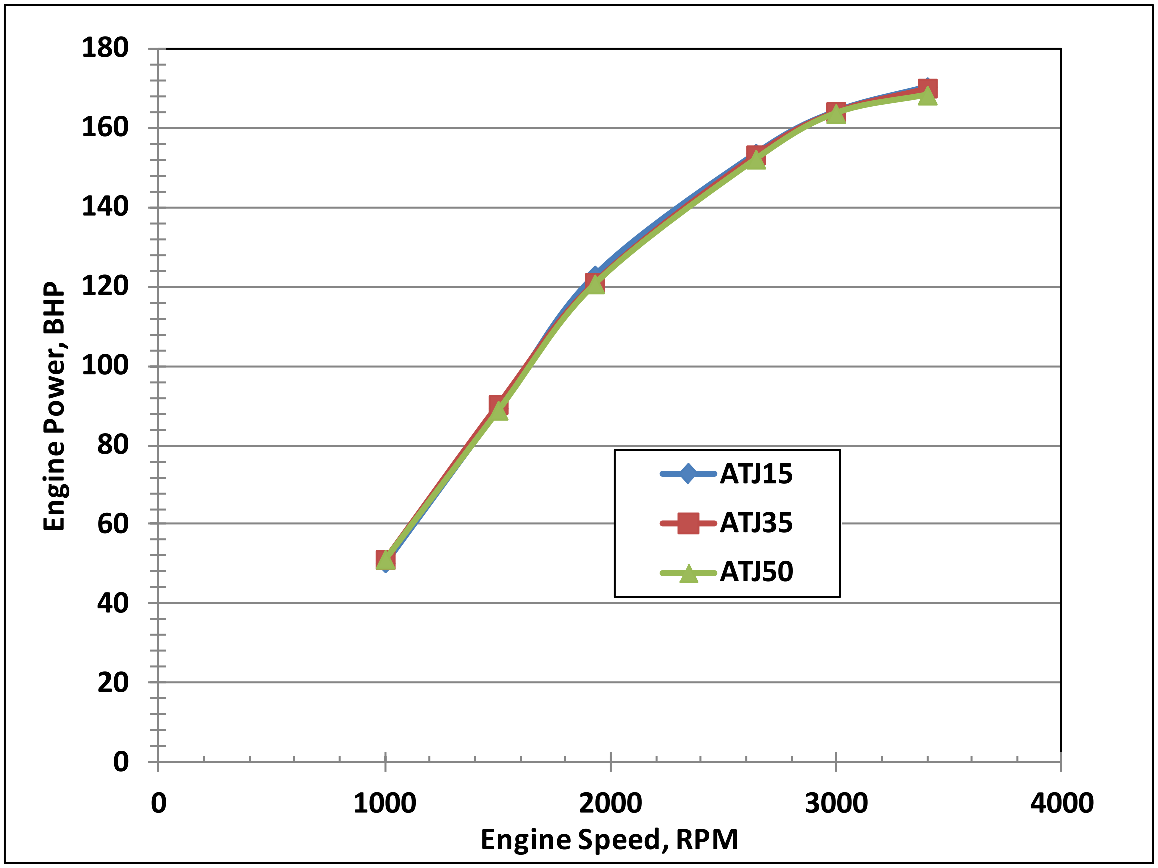


Figure 8. GEP 6.5LT Full Load Brake Power for ATJ/JP-8 Test Fuels

The Brake Specific Fuel Consumption (BSFC) for the full load power curve with the ATJ blends is shown in Figure 9. The ATJ50 fuel reveals a very slightly lower BSFC that may be attributable to its lower cetane number. Fuels with lower cetane number typically have longer ignition delays that result in more premixed fuel combustion. Increased premixed combustion, if close to TDC, can result in increased thermal efficiency and lower BSFC.

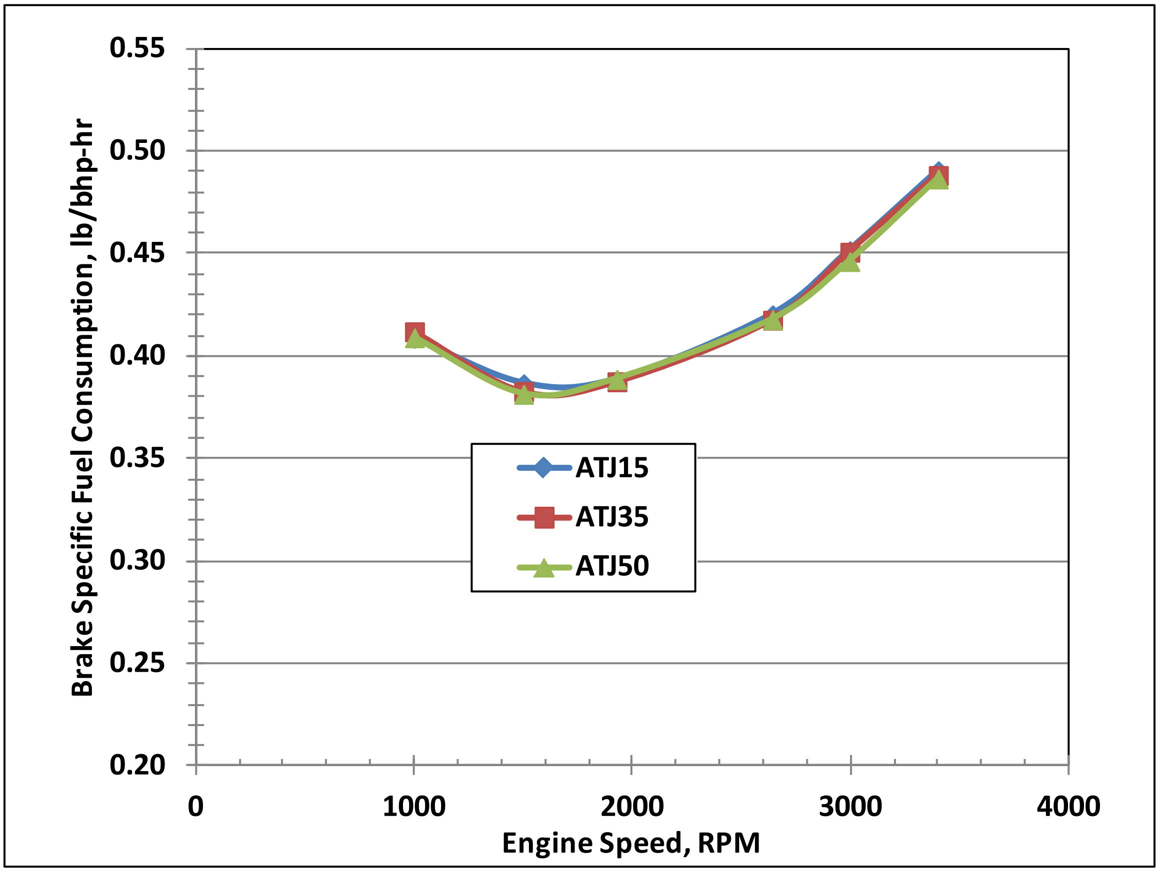


Figure 9. GEP 6.5LT Full Load Brake Specific Fuel Consumption for ATJ/JP-8 Test Fuels

Table 4. Full-Load Operational and Performance Parameters for GEP 6.5LT Engine Operating on ATJ/JP-8 Fuel Blends

Parameter	Units	GEP 6.5LT Test Fuel Blends Full Load Power Curves																	
		ATJ15						ATJ35						ATJ50					
Engine Speed	RPM	1000	1500	1928	2641	2995	3400	1000	1500	1928	2641	2995	3400	1000	1500	1928	2641	2995	3400
Indicated Torque	lb-ft	265	313	335	306	288	263	269	316	330	305	288	263	270	311	329	303	287	260
Power	bhp	50	89	123	154	164	170	51	90	121	153	164	170	51	89	121	152	164	168
Fuel Flow	lb/hr	20.62	34.55	47.77	64.56	74.14	83.59	21.12	34.59	46.95	63.99	73.98	83.02	21.00	33.90	46.92	63.57	73.03	81.87
Mass Air Flow	lb/hr	459.4	839.6	1179	1438	1540	1652	462.0	850.4	1206	1466	1540	1679	456.6	835.4	1184	1452	1548	1670
BSFC	lb/bhp-hr	0.409	0.387	0.389	0.420	0.452	0.491	0.412	0.383	0.388	0.418	0.451	0.488	0.409	0.381	0.389	0.418	0.446	0.487
Coolant Outlet	°F	190.4	190.4	189.1	190.6	190.3	189.9	189.5	189.7	190.1	189.6	190.7	189.7	189.7	190.4	189.9	190.2	190.0	189.8
Oil Sump	°F	204.7	212.4	211.3	224.2	217.4	219.8	212.8	216.3	221.8	220.5	217.3	220.3	215.3	218.2	214.7	213.1	218.1	220.1
Inlet Air	°F	73.8	75.9	75.5	76.0	76.2	75.2	76.5	72.8	77.4	75.5	78.1	75.6	75.7	75.5	74.3	75.4	73.8	76.6
Fuel Inlet	°F	95.5	95.2	93.8	94.0	94.7	94.6	97.8	95.0	97.6	92.5	96.6	91.1	95.6	95.6	96.6	93.3	96.4	94.7
Manifold Air Temperature	°F	116.1	163.5	189.5	170.3	163.5	161.3	115.8	159.8	189.8	169.2	163.1	163.0	114.9	160.3	185.3	168.0	159.5	164.0
Manifold Air Pressure	psia	16.235	20.383	23.065	20.315	19.145	18.363	16.510	20.670	23.224	20.611	19.293	18.772	16.350	20.309	23.140	20.499	19.233	18.644
Intake After Filter	psia	14.204	14.122	14.040	13.956	13.920	13.900	14.421	14.344	14.259	14.178	14.144	14.117	14.346	14.266	14.180	14.100	14.070	14.038
Ambient	psia	14.283	14.281	14.281	14.270	14.270	14.281	14.507	14.507	14.500	14.500	14.490	14.509	14.429	14.428	14.420	14.420	14.420	14.430
Exhaust After Turbo	psia	14.623	14.732	14.928	15.076	15.092	15.041	14.567	14.675	14.879	15.024	15.044	15.054	14.677	14.757	14.827	14.954	14.962	15.065
Oil Gallery	psig	14.671	22.418	32.278	34.841	37.704	39.992	13.142	21.858	30.583	34.160	39.477	39.996	12.875	23.017	32.396	36.469	39.253	39.892
Carbon Monoxide	ppm	268.7	71.2	67.2	91.6	100.4	128.9	211.5	61.2	60.0	76.2	85.2	111.1	137.0	54.2	59.1	73.4	83.5	106.6
Unburned Hydrocarbons	ppm	17.08	16.79	14.61	16.92	14.52	19.97	11.99	10.90	12.76	12.90	14.56	15.45	8.72	9.29	14.48	13.82	15.55	13.90
Oxides of Nitrogen	ppm	348.8	484.0	534.4	543.6	521.0	531.4	403.9	546.5	601.1	598.7	574.5	586.6	443.1	538.9	603.0	596.4	576.2	582.2
Carbon Dioxide	%	10.38	9.36	9.00	9.97	10.65	11.23	10.10	9.11	8.79	9.67	10.48	10.86	10.72	9.58	9.03	10.08	10.86	11.36
Oxygen	%	6.486	7.931	8.424	7.021	6.059	5.350	6.837	8.246	8.658	7.415	6.288	5.818	6.671	8.167	8.863	7.495	6.481	5.860

7.2 FULL LOAD POWER CURVE EMISSIONS

The Brake Specific Hydrocarbon (BSHC) emissions for the full-load power curve points were calculated for each of the ATJ/JP-8 fuel blends and are shown in Figure 10. The ATJ15 blend had higher BSHC emissions likely due to greater aromatics, viscosity, fuel density, and slightly higher T90 temperature. BSHC increases with engine speed due to the shorter time available for combustion completion.

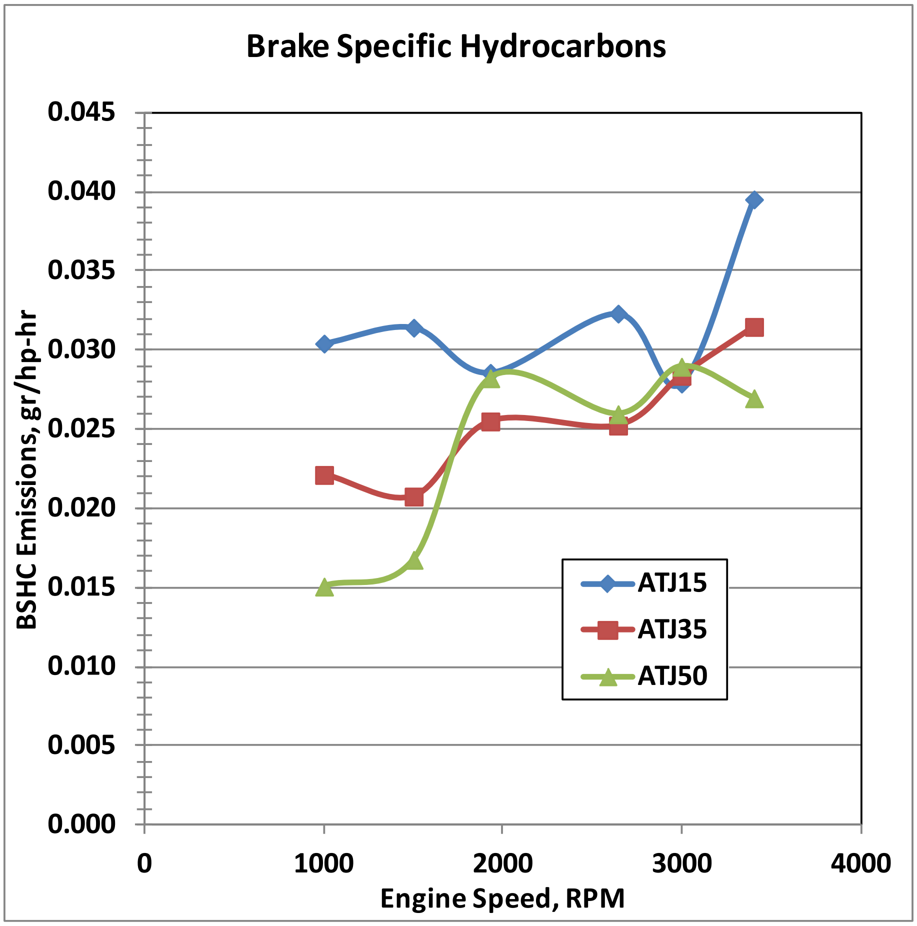


Figure 10. GEP 6.5LT Full Load Brake Specific Hydrocarbon Emissions for ATJ/JP-8 Test Fuels

The Brake Specific Carbon Monoxide (BSCO) emissions shown in Figure 11 for the full-load power curve points were calculated for each of the ATJ/JP-8 fuel blends. The BSCO emissions across the speed range appear to scale inversely with the ATJ content. BSCO emissions are higher at lower speeds due to less fuel/air mixing at the low speed. Improved fuel/air mixing reduces the BSCO emissions, until the BSCO emissions then increase with engine speed due to the shorter time available for combustion completion.

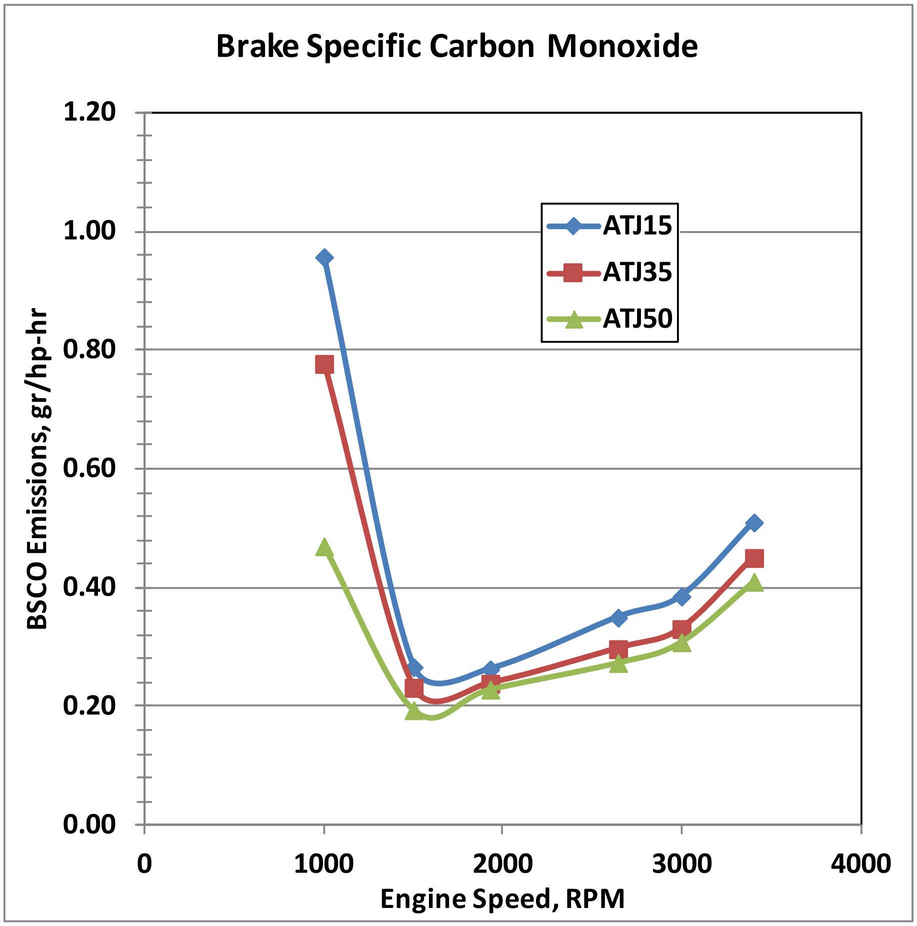


Figure 11. GEP 6.5LT Full Load Brake Specific Carbon Monoxide Emissions for ATJ/JP-8 Test Fuels

The full load power curve Brake Specific Nitrogen Oxides (BSNOx) emissions are shown in Figure 12 for each of the ATJ/JP-8 fuel blends. The BSNOx emissions across the speed range are highest with the ATJ35 fuel blend which had a cetane number between the other two blends. Increased BSNOx is usually a sign of increased premixed combustion that would be anticipated to be seen with the lowest cetane number fuel, in this case ATJ50. Figure 13 shows the ignition delays measured from the start of injection to the start of combustion for each test fuel for the full load power curve. The ATJ50 has the longest ignition delays of the blends. It is possible the ignition delays with the ATJ50 fuel are long enough to delay combustion into a regime of lower flame temperature. NOx formation is highly temperature controlled, thus at low engine speeds with more time available for heat transfer, less fuel/air mixing, then NOx emissions are reduced.

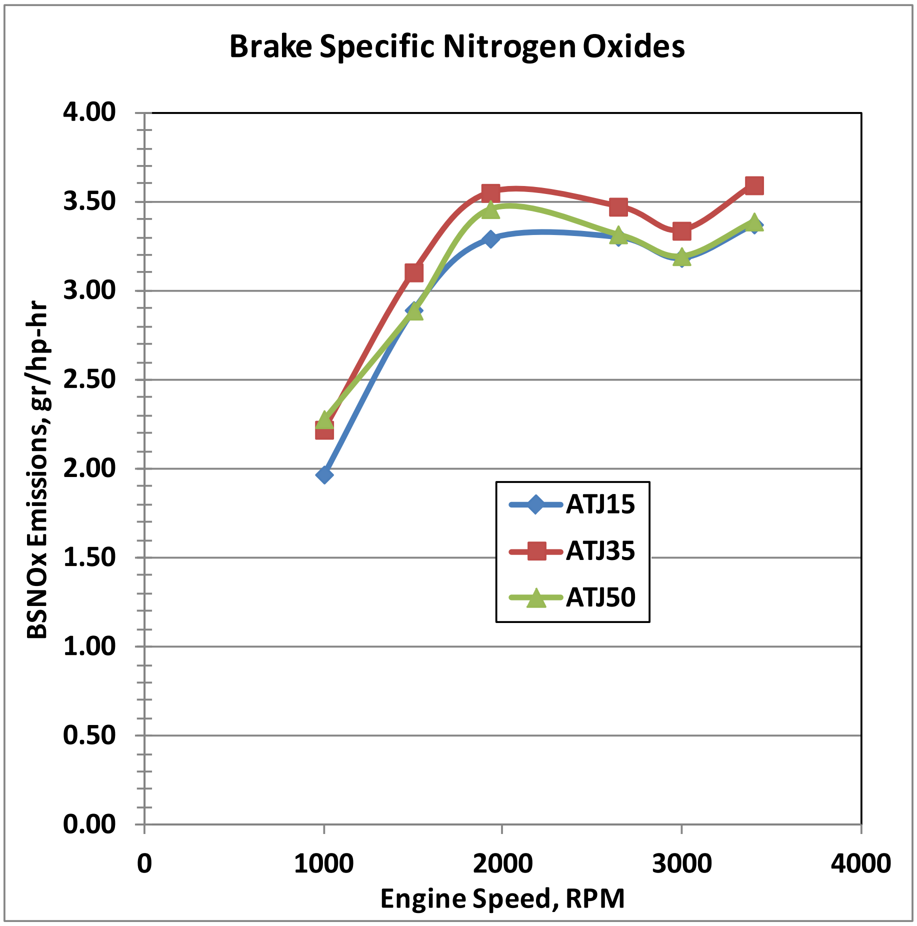


Figure 12. GEP 6.5LT Full Load Brake Specific Nitrogen Oxides Emissions for ATJ/JP-8 Test Fuels

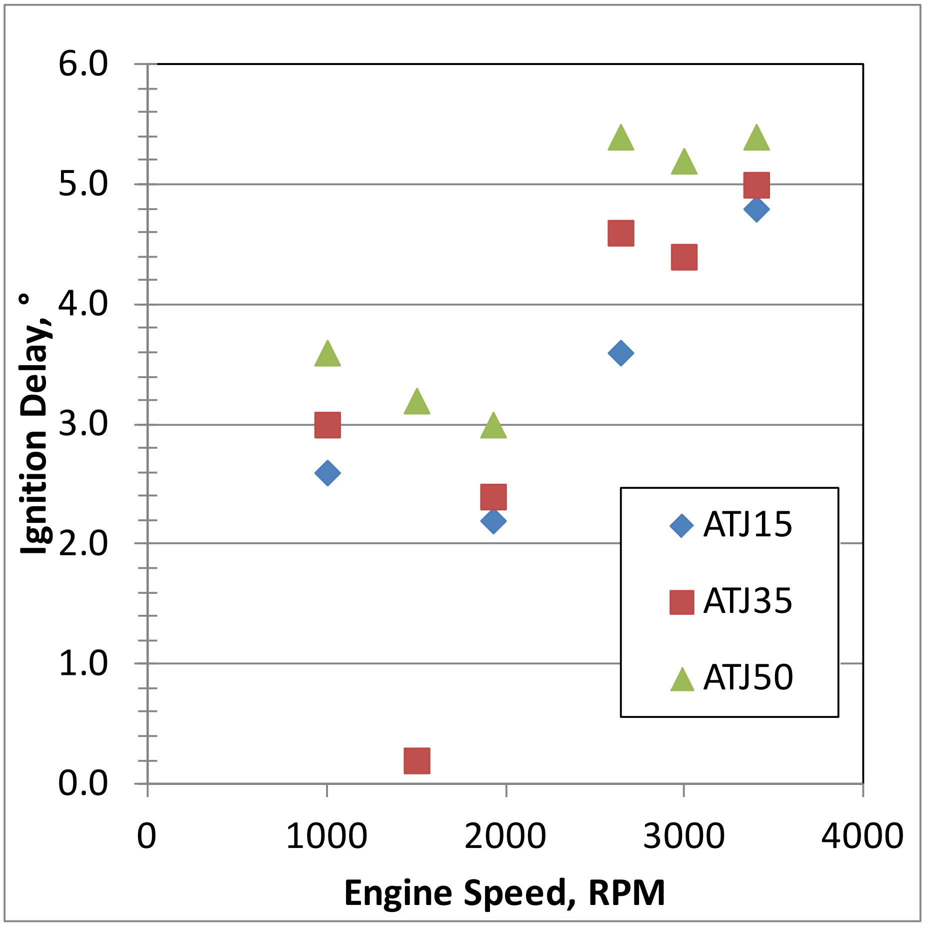


Figure 13. GEP 6.5LT ATJ/JP-8 Fuel Blend Ignition Delay Comparison

An AVL 415 smoke meter was utilized to measure Filter Smoke Number (FSN) for the full load power curve for the ATJ fuel blends. The FSN results are revealed in Figure 14. The FSN reduces with the an increase in ATJ content, likely due to the lowering of fuel density, aromatic content, and fuel sulfur, in addition to the increasing of fuel hydrogen content with increased ATJ content. The FSN decreases as engine speed increases due to the increased turbulent fuel/air mixing.

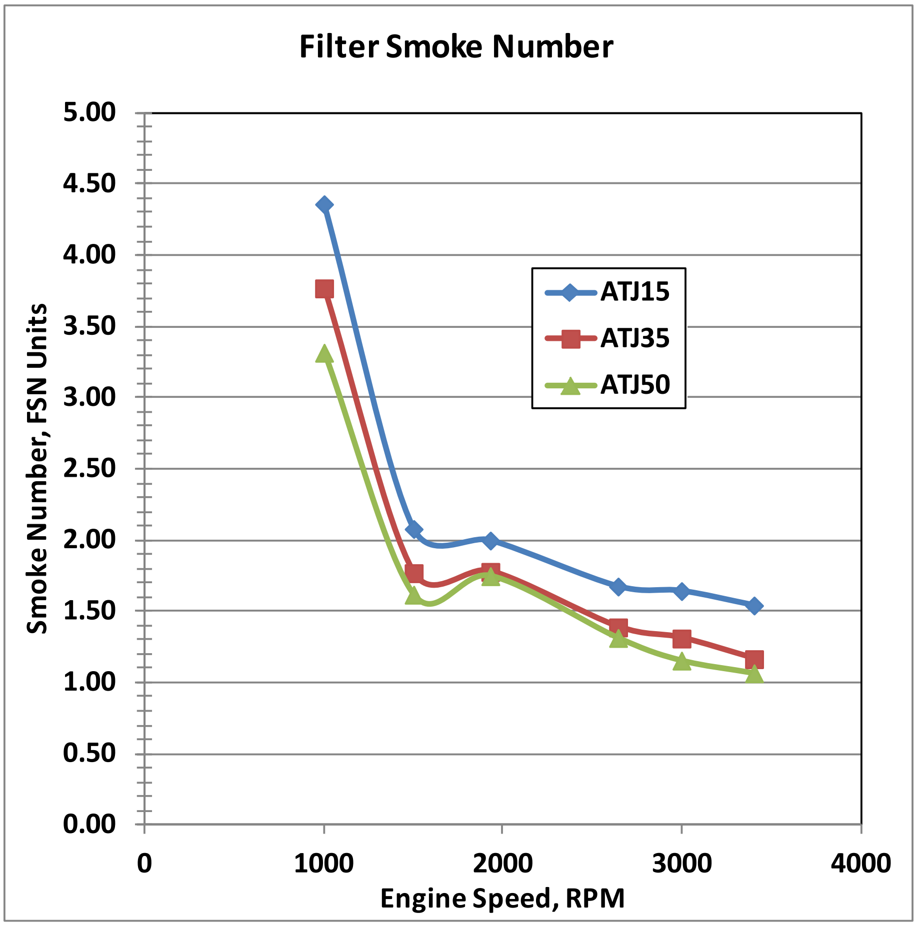


Figure 14. GEP 6.5LT Full Load Filter Smoke Number for ATJ/JP-8 Test Fuels

7.3 ESC WEIGHTED AVERAGE EMISSIONS

The calculated weighted average emissions levels for the ESC for each of the ATJ blends (as seen in Figure 15) were below the Non-Road Tier 1 standard of 6.9 g/bhp-hr NOx. In addition the HC and CO emissions also did not exceed the Non-Road Tier 1 standards of 1.0 g/bhp-hr HC and 8.5 g/bhp-hr CO. Also included in Figure 15 is a weighted average FSN for the ATJ blends.

Except for the NOx emissions, the ESC weighted average emissions scale with the ATJ content in the blend. HC and CO increase with ATJ content, and FSN decreases with ATJ content. Interestingly the ATJ35 blend reveals the highest ESC weighted average NOx, which compares to the ATJ35 having the highest BSNOx for the full load power curves.

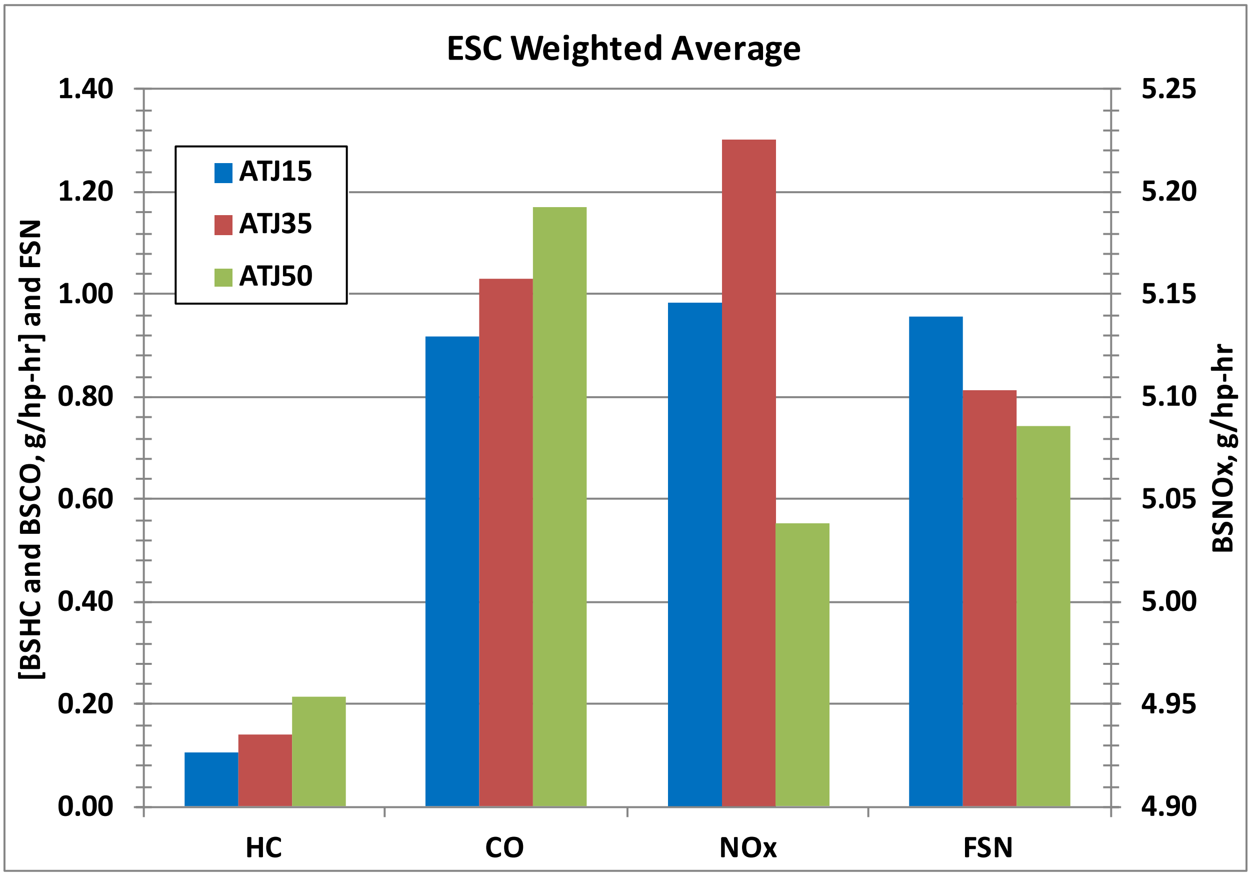


Figure 15. GEP 6.5LT 13-Mode European Stationary Cycle Weighted Average Emissions for ATJ/JP-8 Test Fuels

8.0 COMBUSTION CHARACTERISTICS

8.1 GEP 6.5LT ENGINE OPERATING ON ATJ/JP-8 BLENDS

For the combustion data analyzed for the GEP 6.5LT engine, to stay consistent with a prior study only the pre-chamber data was used. This is due largely to the ignition event taking place inside the pre-chamber. Data presented in Table 5, and the subsequent heat release plots are from the main chamber transducer. The main chamber heat release was plotted to reflect the work performed on the piston by each ATJ fuel blend. The following discussion refers only to the full load power curve data point plots , all additional ESC data plots are available in APPENDIX A.

Table 5. GEP 6.5LT Full Load Power Curve Main Chamber ATJ Blend Combustion Data Summary

Parameter	3400-RPM			2995-RPM			2641-RPM			1928-RPM			1500-RPM			1000-RPM		
Fuel:	ATJ15	ATJ35	ATJ50	ATJ15	ATJ35	ATJ50	ATJ15	ATJ35	ATJ50	ATJ15	ATJ35	ATJ50	ATJ15	ATJ35	ATJ50	ATJ15	ATJ35	ATJ50
Run#:	810	826	842	822	838	854	820	836	852	814	830	846	811	827	843	812	828	844
Cylinder Name	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC	Cyl-1MC
MaxPress (bar)	86.01159	86.98728	86.45264	87.90935	89.06351	89.83426	94.07847	94.80402	94.05972	103.3589	102.1304	101.3604	93.15378	92.97335	92.45721	75.64611	77.58325	78.64208
MaxPressPos (°ATDC)	9.4	9.6	10.2	10	10	10.2	9	9.2	9.4	8.8	9.2	8.8	9.6	9.8	7.8	6.2	6.6	6.8
MaxPressRise (bar/°)	2.558894	2.618973	2.617541	2.496877	2.536815	2.554602	2.652329	2.658165	2.642503	2.783277	2.816015	2.789179	3.208891	3.236182	3.673508	3.708364	3.861615	4.553429
MaxPressRisePos (°ATDC)	-14.2	-14.2	-14.2	-13.4	-13.4	-13.4	-13.8	-13.8	-13.8	-13.8	-13.8	-13.6	4.6	4.8	4.8	-1	-0.6	0.2
Peg (bar)	1.141648	1.178284	1.164764	1.171576	1.202577	1.20331	1.267093	1.301285	1.281406	1.47232	1.503465	1.483065	1.285943	1.338088	1.318354	0.992848	1.050928	1.034194
Indicated Power (kW)	18.71371	19.09161	18.93162	18.13529	18.5565	18.50591	16.43526	17.19226	17.09351	12.64562	13.47775	13.39286	9.110727	9.927441	9.613394	4.754968	5.456266	5.477756
gIMEP (bar)	8.02331	8.092581	8.024166	8.538931	8.465217	8.459048	8.843758	8.790311	8.724693	9.166482	8.968449	8.910745	8.300918	8.370558	8.124822	6.67616	6.80011	6.888584
nIMEP (bar)	8.479384	8.504846	8.433571	9.281095	9.169397	9.142325	9.766447	9.636573	9.577936	10.5959	10.35977	10.28966	9.724904	9.808516	9.498276	7.946589	8.106379	8.1344
pIMEP (bar)	0.456074	0.412264	0.409406	0.742164	0.70418	0.683277	0.922689	0.846262	0.853243	1.429414	1.391317	1.378915	1.423985	1.437958	1.373454	1.270429	1.306269	1.245815
MaxCumHeat (kJ)	1.358657	1.346227	1.330967	1.441629	1.420226	1.405746	1.44276	1.42089	1.402421	1.486959	1.446464	1.439286	1.345247	1.353405	1.311707	1.126807	1.134403	1.144168
MaxHeatRel (J/°)	56.58619	60.14746	64.21176	64.45483	71.2927	75.50446	65.47912	71.69827	75.02391	79.41964	80.69338	75.00739	79.0592	80.73964	87.05225	54.64714	58.27492	73.03222
SOCAng (°ATDC)	-1.8	-1.2	-0.8	-1.6	-1.2	-0.6	-3	-1.8	-1.2	-3.6	-2.8	-2.4	-5.2	-5	-1.8	-3.8	-3.4	-2.8
EOCAng (°ATDC)	85	80.6	80.6	79.2	79	79.4	63.4	56	56	57.6	56.4	57	54	51.4	50.8	65.4	69	61.2
MFB 02Angle (°ATDC)	1.095871	1.620781	2.078946	1.505789	1.953816	2.260378	0.497414	1.255556	1.70345	-0.85386	0.091527	0.534381	-0.82743	-0.17969	0.552561	-2.20155	-1.85993	-1.27034
MFB 10Angle (°ATDC)	4.447829	4.863088	5.195185	4.806735	5.044846	5.159094	3.807915	4.255407	4.485206	3.178842	4.007195	3.815398	2.42783	2.954451	3.187345	-0.37444	-0.12632	0.259554
MFB 50Angle (°ATDC)	17.87581	17.52947	17.27712	16.7606	16.5997	15.95924	15.38769	14.79503	14.66265	13.32107	13.54753	13.66011	12.00897	12.5968	12.1901	14.0443	13.03251	11.44789
MFB 90Angle (°ATDC)	45.27808	42.52322	42.08361	43.54619	42.61939	41.41656	38.74568	36.53277	35.98384	34.69306	33.30046	33.07773	34.48493	33.27052	32.9529	40.77523	39.18826	38.42355
MFB 0-2 Duration	2.89587	2.820781	2.878946	3.105789	3.153816	2.860378	3.497414	3.055556	2.90345	2.746141	2.891527	2.934381	4.372574	4.820308	2.352561	1.598448	1.540066	1.529664
MFB 0-10 Duration	6.247829	6.063088	5.995185	6.406735	6.244846	5.759094	6.807915	6.055407	5.685206	6.778842	6.807195	6.215398	7.62783	7.954451	4.987345	3.425563	3.273678	3.059554
MFB 0-50 Duration	19.67581	18.72947	18.07712	18.3606	17.7997	16.55924	18.38769	16.59503	15.86265	16.92107	16.34753	16.06011	17.20897	17.5968	13.9901	17.8443	16.43251	14.24789
MFB 2-10 Duration	3.351958	3.242307	3.11624	3.300947	3.09103	2.898715	3.310501	2.999851	2.781756	4.0327	3.915667	3.281017	3.255256	3.134143	2.634784	1.827115	1.733612	1.52989
MFB 10-90 Duration	40.83025	37.66013	36.88842	38.73945	37.57455	36.25746	34.93776	32.27736	31.49863	31.51422	29.29327	29.26233	32.0571	30.31607	29.76555	41.14967	39.31458	38.164
gIMEPAvg (bar)	8.02331	8.092581	8.024166	8.538931	8.465217	8.459048	8.843758	8.790311	8.724693	9.166482	8.968449	8.910745	8.300919	8.370558	8.124822	6.67616	6.80011	6.888584
gIMEPSTD (bar)	0.111548	0.101523	0.121101	0.114718	0.10818	0.113321	0.117182	0.108029	0.117498	7.62E-02	7.11E-02	8.59E-02	0.119357	0.107665	0.112677	0.113393	0.150031	0.102698
gIMEPCOV (%)	1.3903	1.254515	1.509208	1.343473	1.277934	1.339645	1.325028	1.22896	1.346728	0.830876	0.792444	0.963568	1.437874	1.286231	1.386819	1.698474	2.206296	1.490846
Compression PolyTrope	1.482523	1.492082	1.488702	1.496976	1.486015	1.488631	1.450269	1.469322	1.469664	1.43375	1.440035	1.444161	1.431593	1.429082	1.430345	1.420944	1.421521	1.421976
Expansion PolyTrope	1.135583	1.155834	1.163267	1.154889	1.162076	1.172719	1.200584	1.230664	1.232574	1.249377	1.264117	1.265885	1.249346	1.25714	1.26763	1.177657	1.197637	1.211048
SOI Timing 1 (°ATDC)	-6.6	-6.2	-6.2	-6	-5.6	-5.8	-6.6	-6.4	-6.6	-5.8	-5.2	-5.4	-5.4	-5.2	-5	-6.4	-6.4	-6.4
SOI Timing 2 (°ATDC)	25.6	46.4	46	23.8	24.2	24.2	40.6	40.8	40.6	33.2	34.2	33.6	19.4	19.8	20.2			
SOI Timing 3 (°ATDC)	46.2	57.8	57	43.8	44.2	44												
EOI Timing 1 (°ATDC)	24.6	27.2	27	23	22.8	23	20.6	20.6	20.4	19.2	20	20	19	19.4	19.8	17	17.2	17.4
EOI Timing 2 (°ATDC)	26	56.4	56.4	25.2	24.6	25.2	46	46.4	47	37.8	39	38.6	20.6	21	21.2			
EOI Timing 3 (°ATDC)	55	58.2	58.8	50.8	51.6	51.4												
Ignition Delay (°)	4.8	5	5.4	4.4	4.4	5.2	3.6	4.6	5.4	2.2	2.4	3	0.2	0.2	3.2	2.6	3	3.6

Figure 16 shows the main-chamber pressure traces for the GEP 6.5LT engine at the rated power condition on the ATJ blends. The peak pressures are similar in the main-chamber, but there appears to be a heat transfer or combustion phasing differnce between the blends.

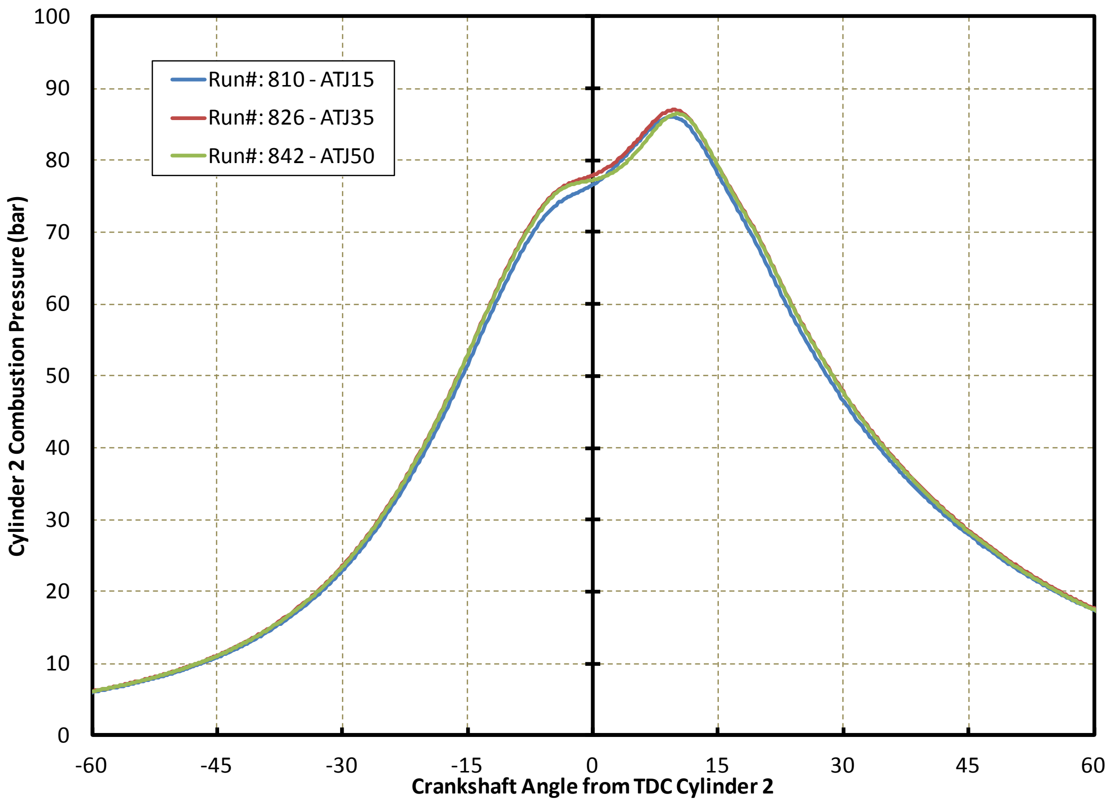


Figure 16. Main Chamber Pressure Histories for 3,400-RPM and 100% Load

Figure 17 shows the pre-chamber pressure traces for the GEP 6.5LT engine at the rated power condition on the ATJ blends. The peak pressures are higher with increased ATJ content blends in the pre-chamber. Also a heat transfer or combustion phasing difference is seen between the blends.

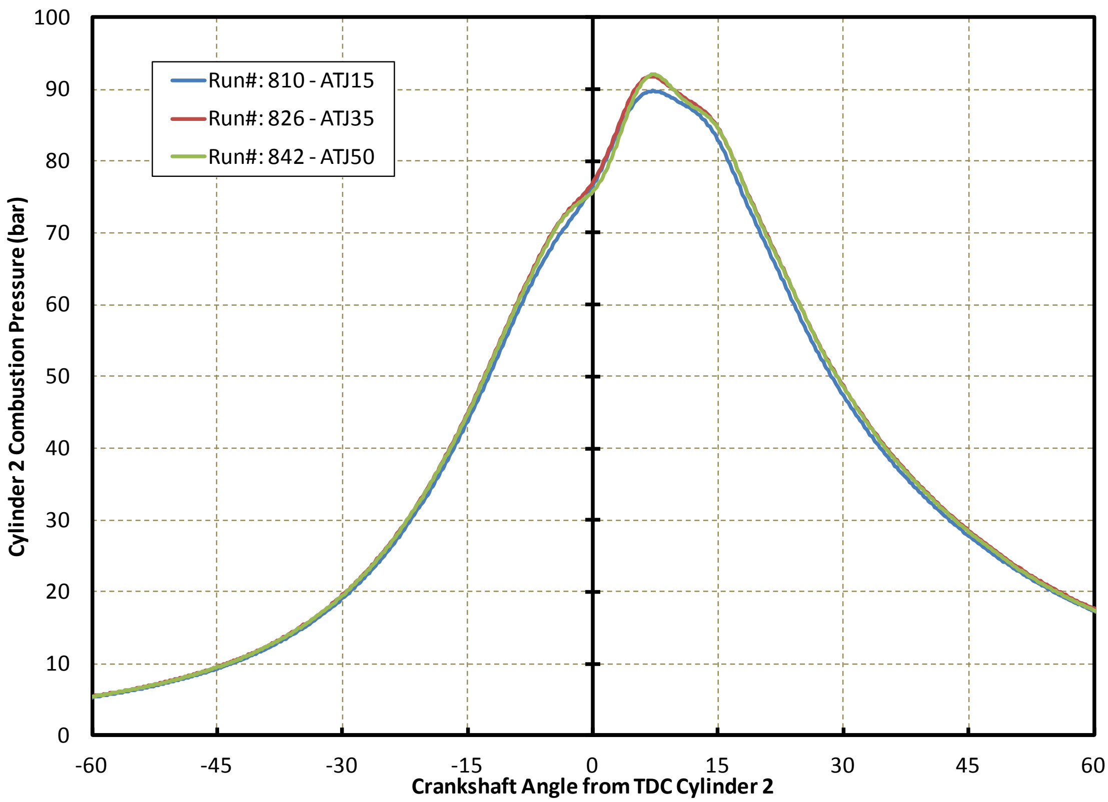


Figure 17. Pre-Chamber Pressure Histories for 3,400-RPM and 100% Load

The apparent Heat Release Rates (HRR) calculated from the main chamber pressure traces are shown in Figure 18 for the rated speed condition for the ATJ blends. Included in the plots are the injector needle lift that shows identical start of injection for each ATJ blend and secondary injections. The ATJ35 and ATJ50 blends appear to ignite later but exhibit a faster burn rate, with higher maximum HRR. The location of the maximum HRR appears to be at the same crankshaft angle with respect to TDC.

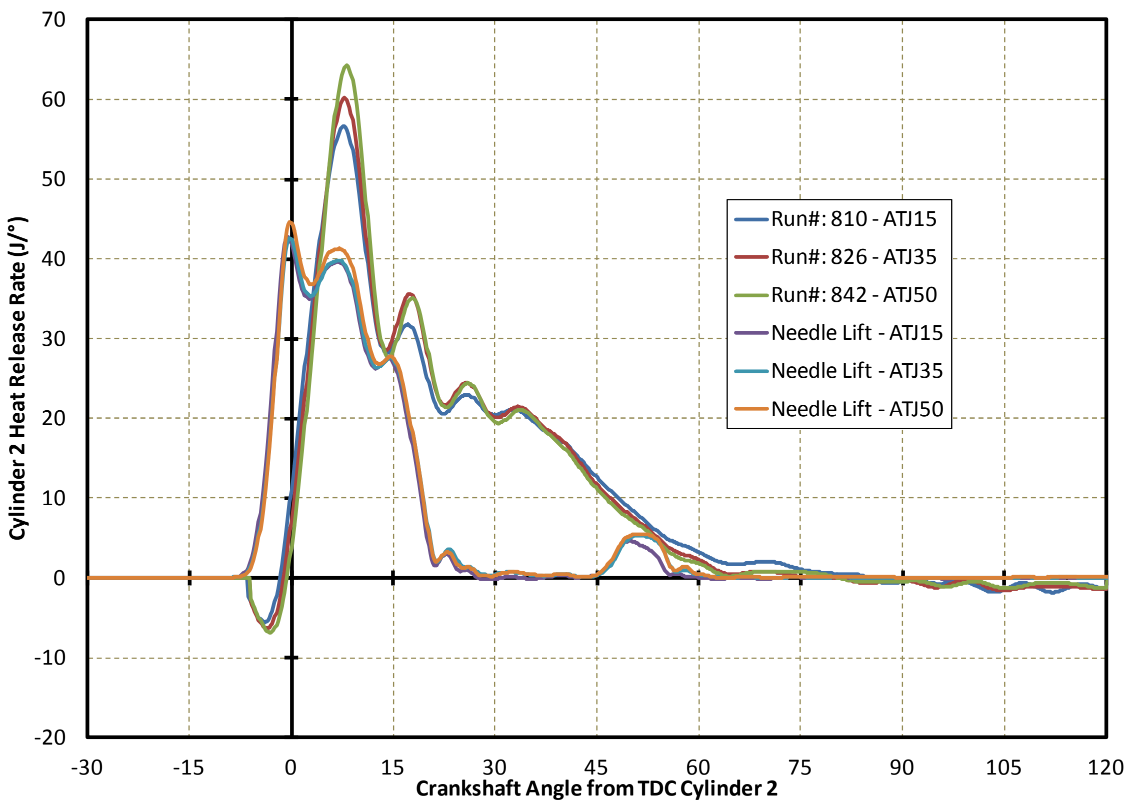


Figure 18. Heat Release Rate Histories for 3,400-RPM and 100% Load

The Mass Fraction Burned (MFB) curve is shown in Figure 19 for the rated power condition for each ATJ blend. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. The faster burn rates of the ATJ35 and ATJ50 fuels are seen from 45%MFB on, whereas the ATJ15 burns later into the engine cycle.

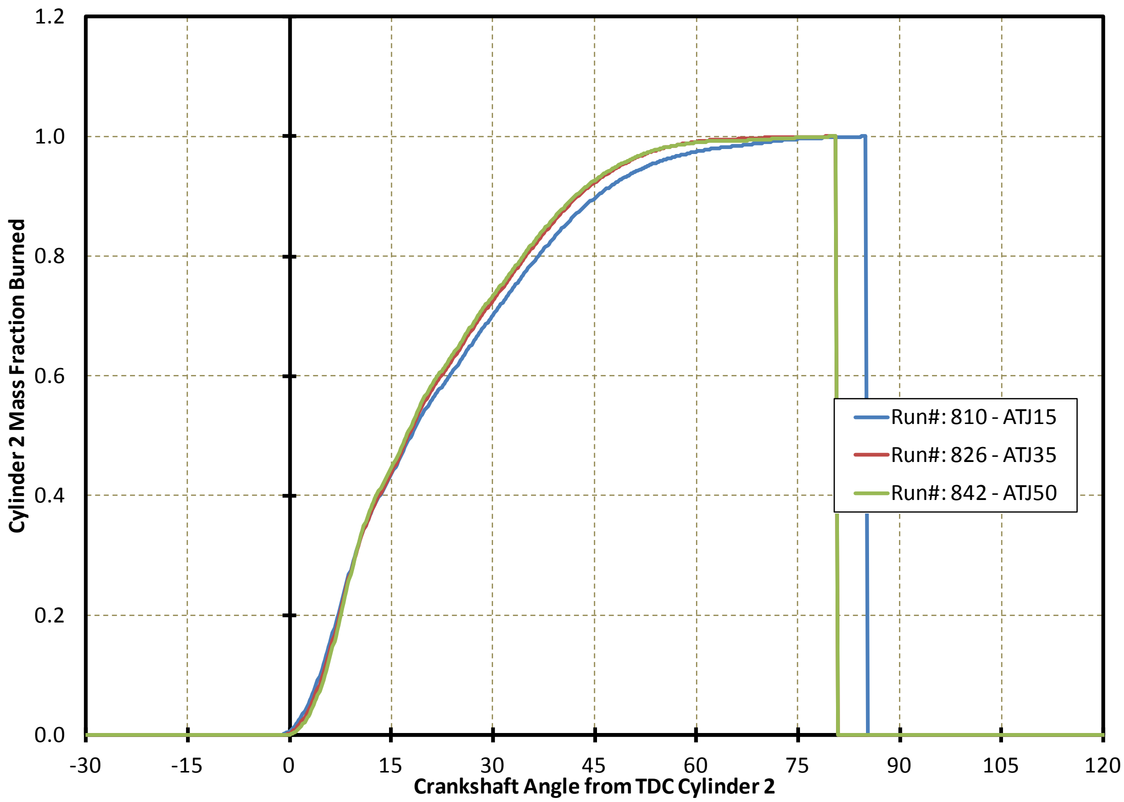


Figure 19. Fuel Mass Fraction Burned for 3,400-RPM and 100% Load

Figure 20 are the main-chamber pressure traces for the GEP 6.5LT engine at the full load condition for the 2,995-RPM power condition on the ATJ blends. This condition is Mode 10 of the ESC. The pressure development pre-burn is similar, with peak pressure from combustion increasing with increasing fuel ATJ content.

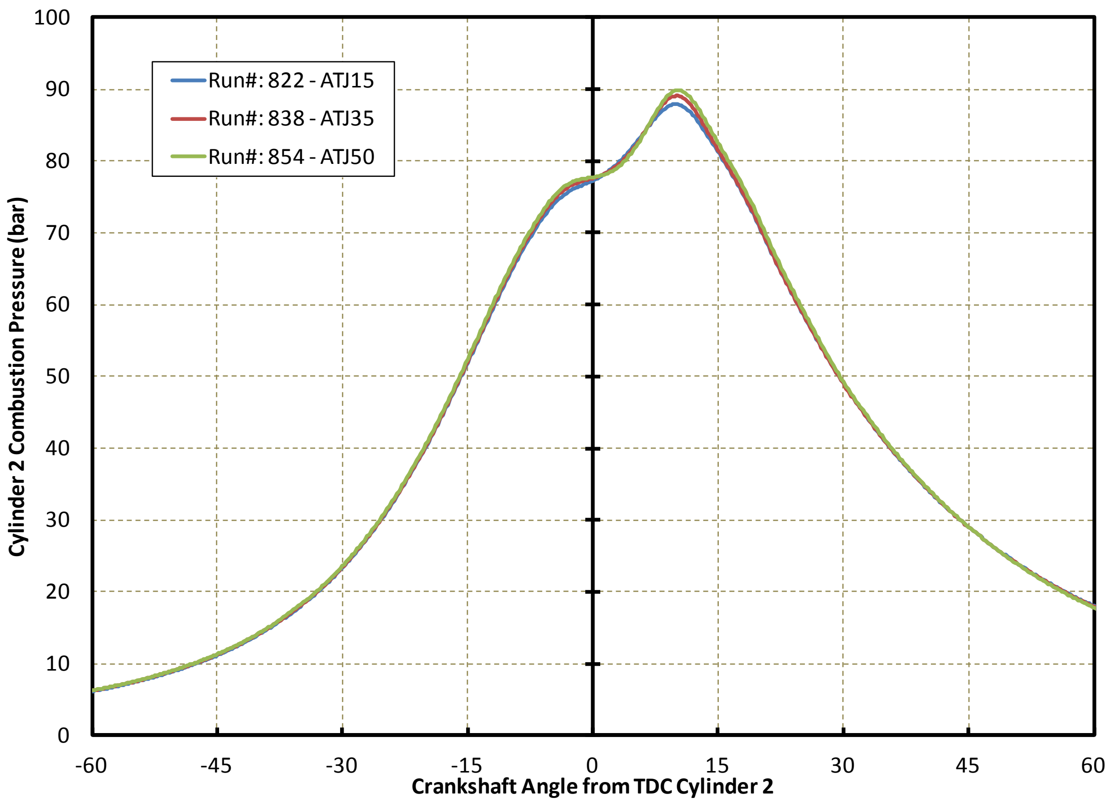


Figure 20. Main Chamber Pressure Histories for 2,995-RPM and 100% Load, ESC10

Figure 21 are the pre-chamber pressure traces for the GEP 6.5LT engine at the 2,995-RPM full load power condition on the ATJ blends. The peak pressures are higher with increased ATJ content blends in the pre-chamber. The pressure development pre-burn is similar, with peak pressure from combustion increasing with increasing fuel ATJ content. ATJ15 appears to approach constant pressure combustion.

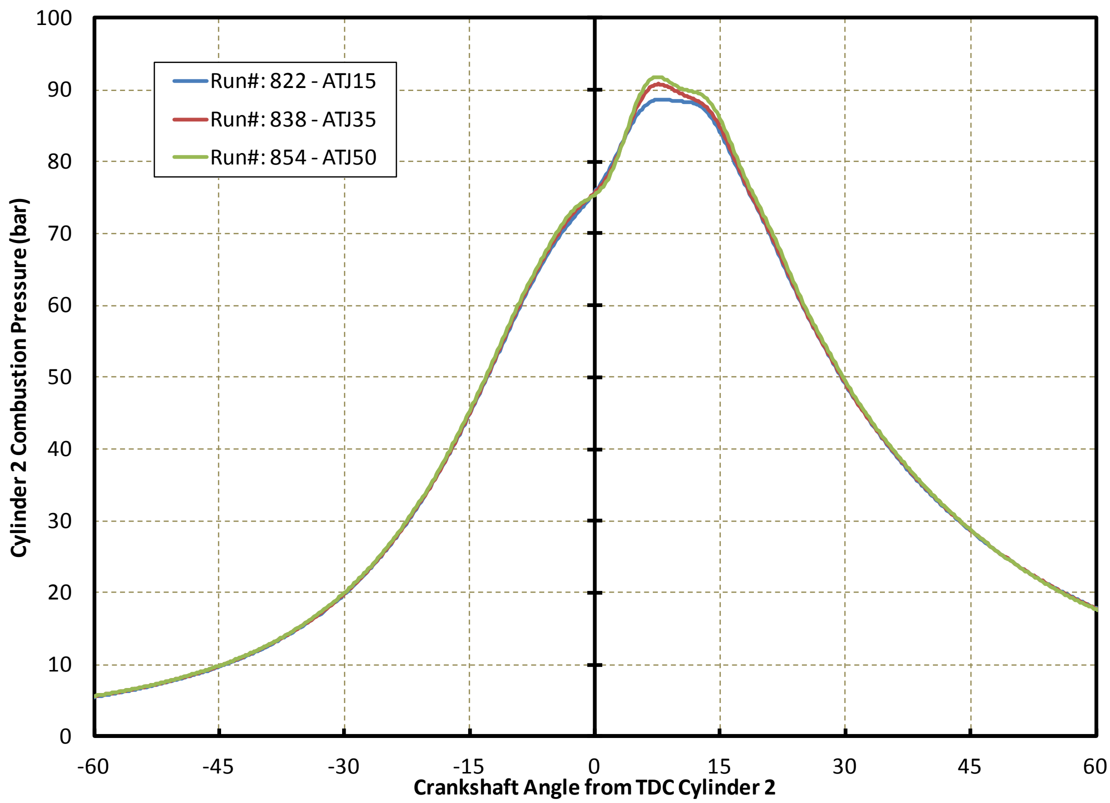


Figure 21. Pre-Chamber Pressure Histories for 2,995-RPM and 100% Load, ESC10

The apparent Heat Release Rates (HRR) calculated from the main chamber pressure traces are shown in Figure 22 for the 2,995-RPM condition for the ATJ blends. Included in the plots are the injector needle lift that shows identical start of injection for each ATJ blend and secondary injections. The maximum HRR scales with ATJ content are also shown. The ATJ50 blends appear to ignite later but exhibits a faster burn rate, with higher maximum HRR. The location of the maximum HRR appears to be at the same crankshaft angle with respect to TDC.

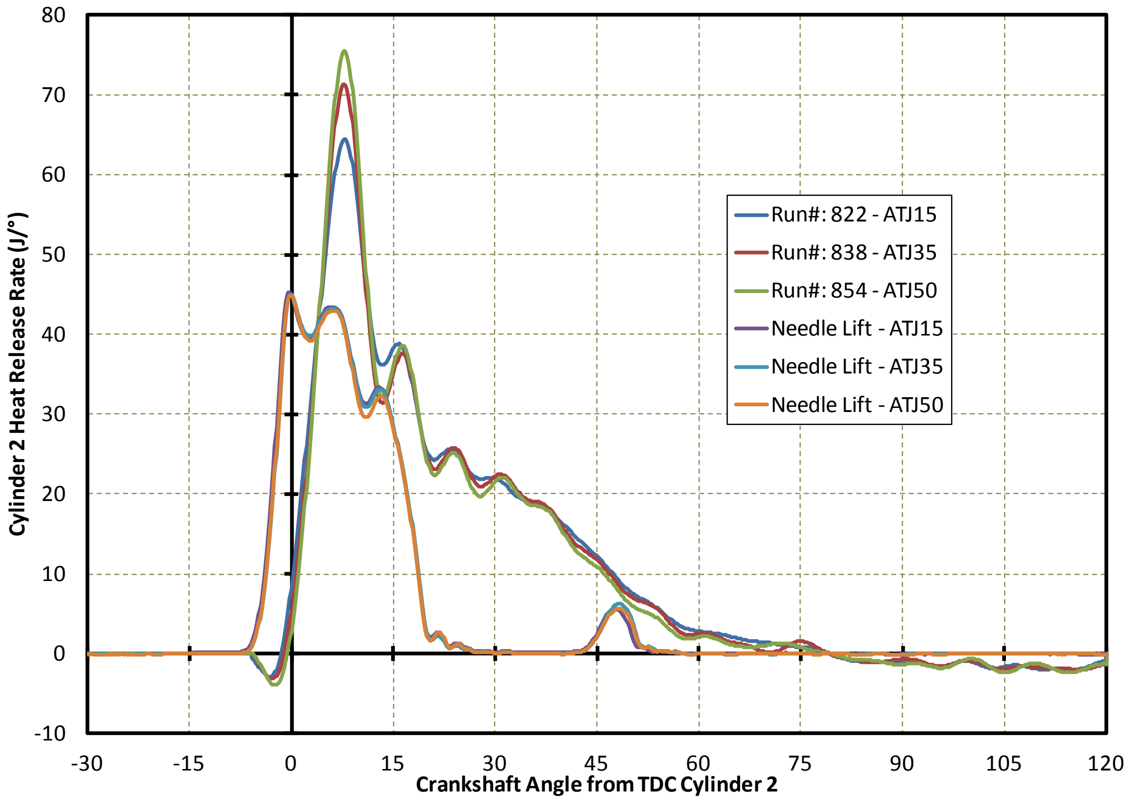


Figure 22. Heat Release Rate Histories for 2,995-RPM and 100% Load, ESC10

The Mass Fraction Burned (MFB) curve is shown in Figure 23 for the 2,995-RPM full load power condition for each ATJ blend. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. The burn rates of the ATJ15 and ATJ35 fuels are similar. The ATJ50 burn is initially delayed, but the 40-90% MFB for ATJ50 occurs over shorter crankshaft angle duration.

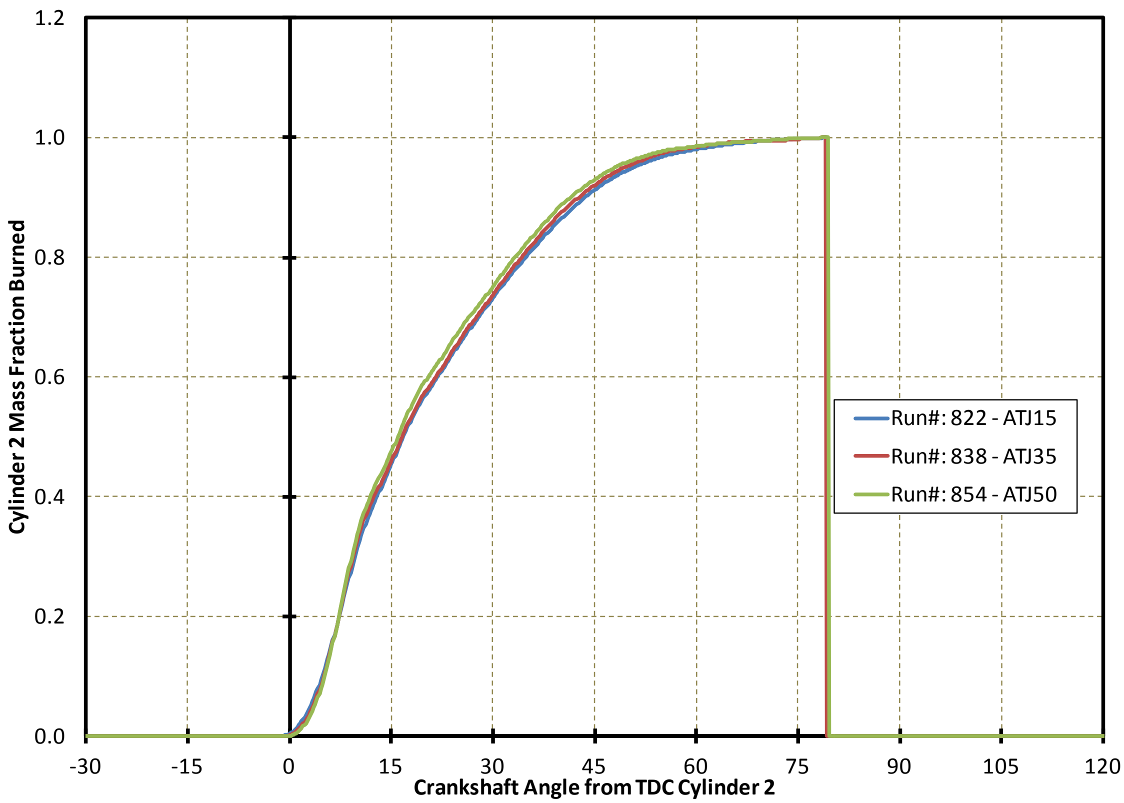


Figure 23. Fuel Mass Fraction Burned for 2,995-RPM and 100% Load, ESC10

Figure 24 are the main-chamber pressure traces for the GEP 6.5LT engine at the full load condition for the 2,641-RPM power condition on the ATJ blends. This condition is Mode 8 of the ESC. For this operating condition the ATJ35 fuel blend exhibits the highest main chamber peak cylinder pressure.

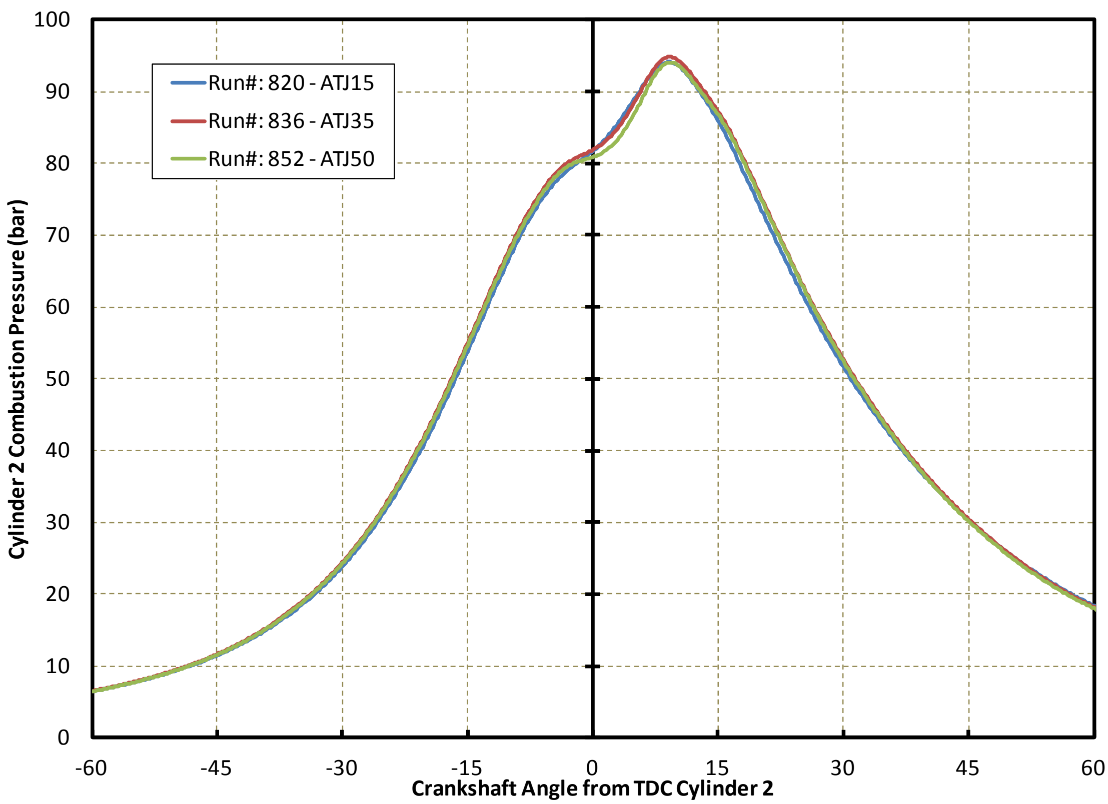


Figure 24. Main Chamber Pressure Histories for 2,641-RPM and 100% Load, ESC8

Figure 25 are the pre-chamber pressure traces for the GEP 6.5LT engine at the 2,641-RPM power condition on the ATJ blends. The peak pressures are higher with increased ATJ content blends in the pre-chamber. ATJ35 also ehibits the highest peak presure in the pre-chamber, and appears to have a faster pressure rise rate. The three ATJ blends approach constant pressure combustion in the pre-chamber.

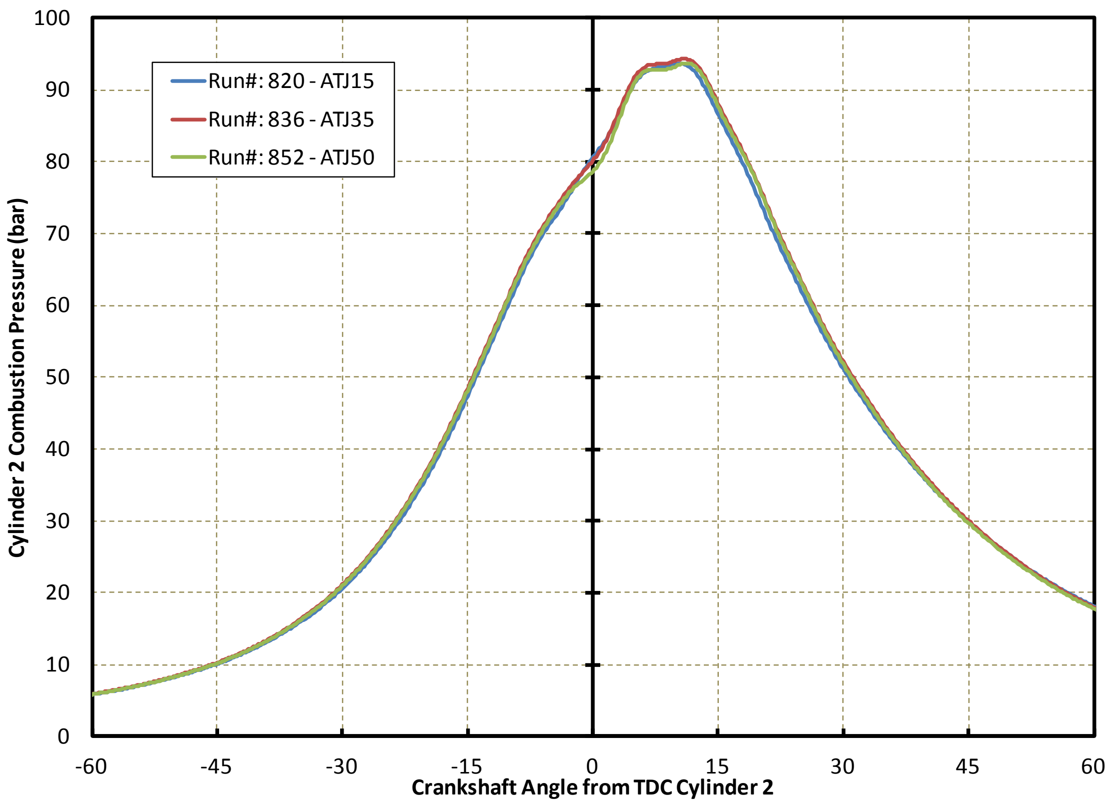


Figure 25. Pre-Chamber Pressure Histories for 2,641-RPM and 100% Load, ESC8

The apparent Heat Release Rates (HRR) calculated from the main chamber pressure traces are shown in Figure 26 for the 2,641-RPM power condition for the ATJ blends. Included in the plots are the injector needle lift that shows identical start of injection for each ATJ blend and secondary injections. The ATJ35 has the higher initial burn rate, but ultimately the ATJ50 fuel has the highest maximum HRR. The location of the maximum HRR appears to be at the same crankshaft angle with respect to TDC for each blend. The ATJ15 fuel exhibits more diffusion controlled burn, evidenced by the higher burn rates later in the cycle.

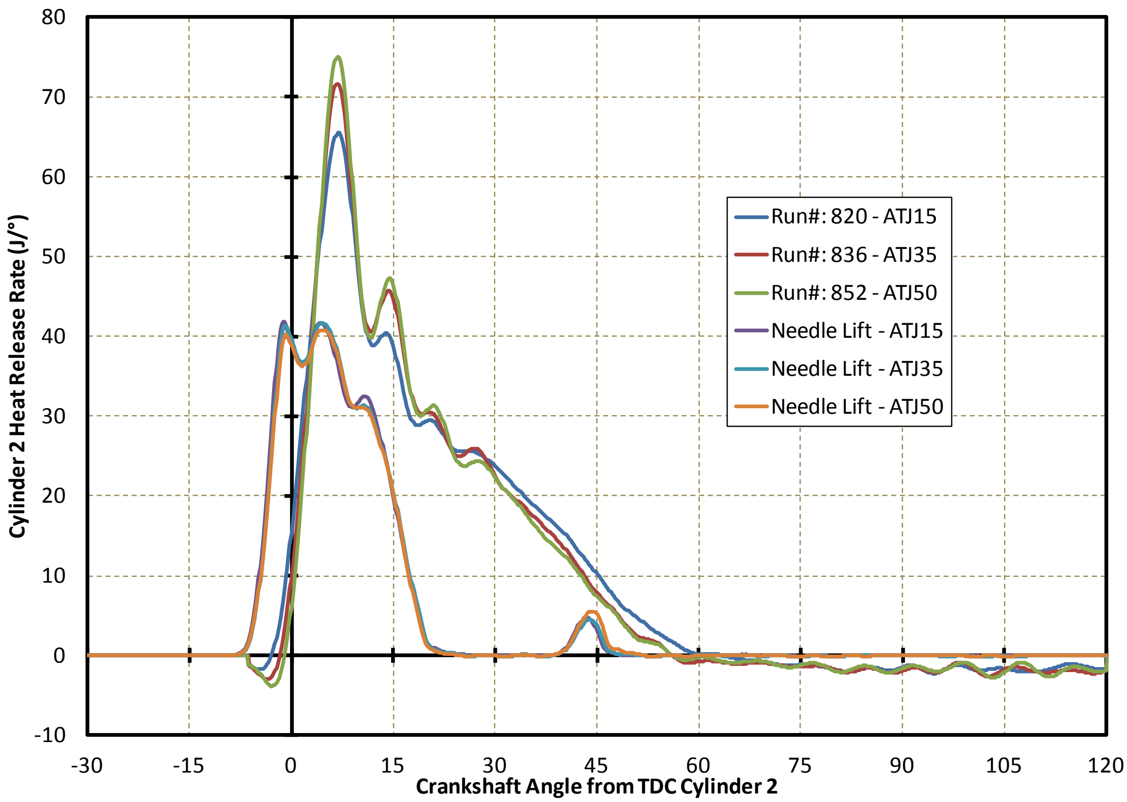


Figure 26. Heat Release Rate Histories for 2,641-RPM and 100% Load, ESC8

The Mass Fraction Burned (MFB) curve is shown in Figure 27 for the 2,641-RPM full load power condition for each ATJ blend. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. The MFB curves for the ATJ35 and ATJ50 fuels are very similar, with a slight delay from the ATJ15 fuel, than shorter burn duration to completion. Whereas the ATJ15 fuel burns over a longer duration and later into the engine combustion cycle.

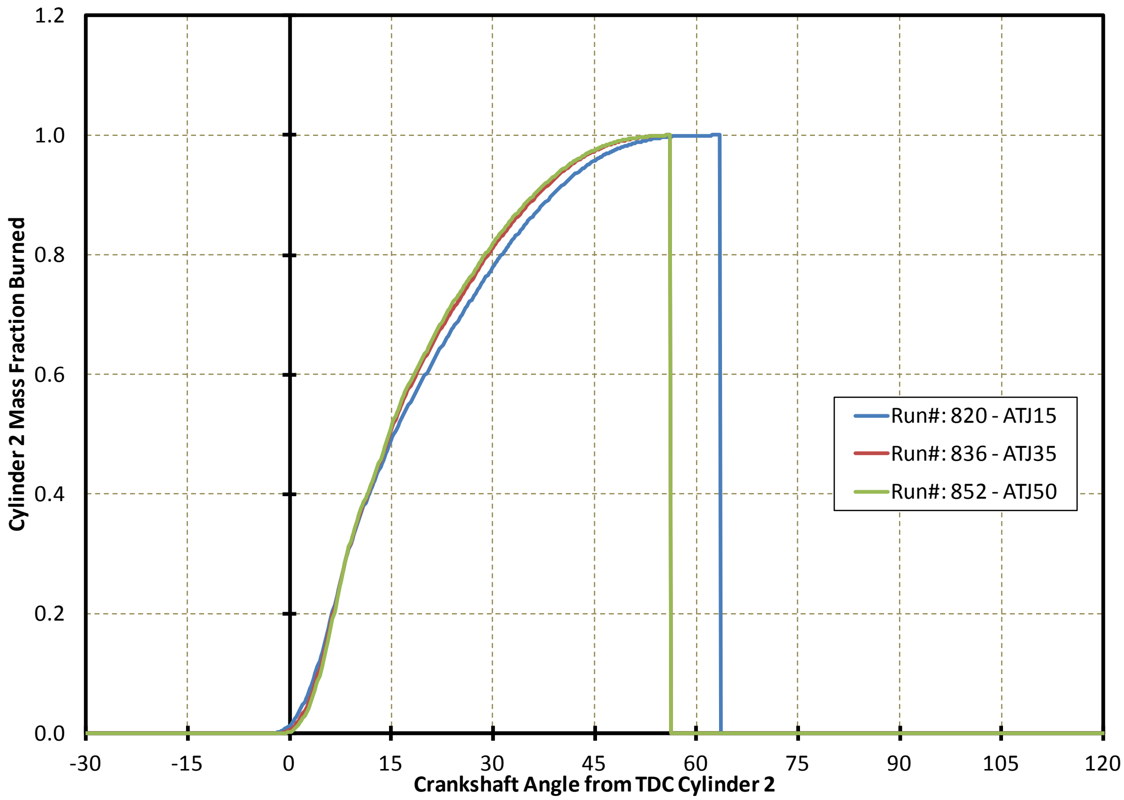


Figure 27. Fuel Mass Fraction Burned for 2,641-RPM and 100% Load, ESC8

Figure 28 are the main-chamber pressure traces for the GEP 6.5LT engine at the full load condition for the 1,928-RPM power condition on the ATJ blends. This condition is Mode 2 of the ESC. The peak pressures are highest with the ATJ15 blend in the main chamber. The other two ATJ blends reveal similar pressure development and lower peak pressures.

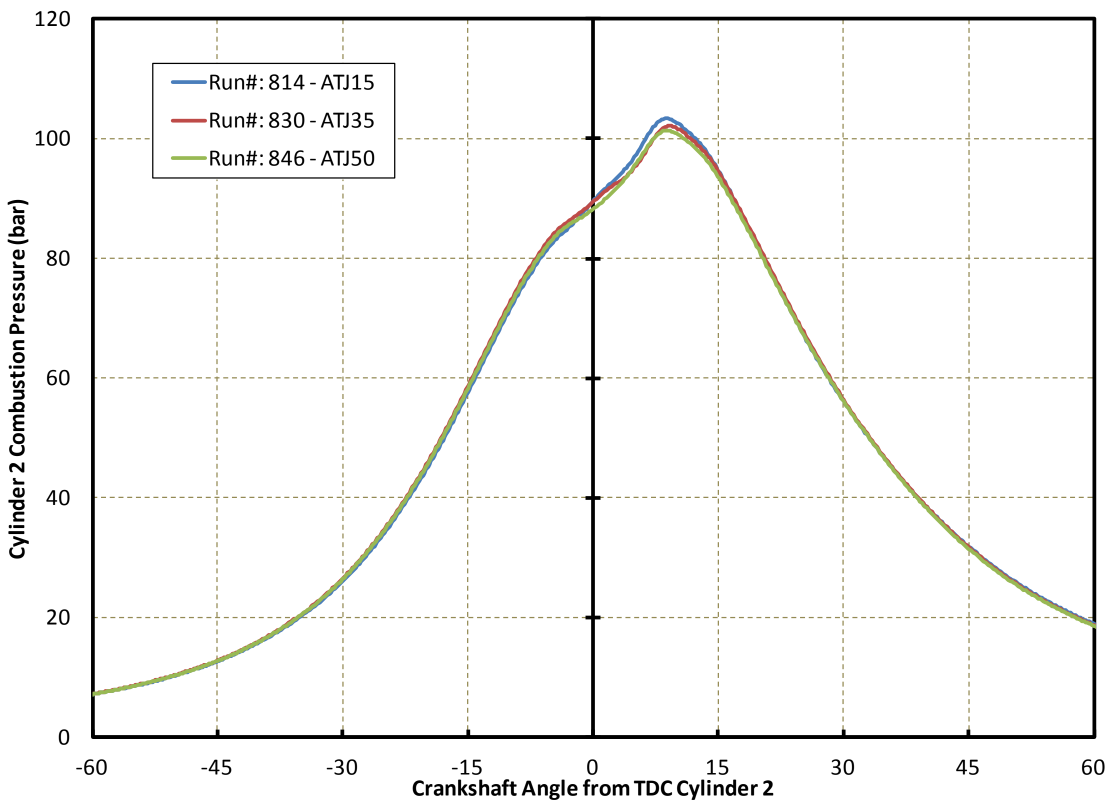


Figure 28. Main Chamber Pressure Histories for 1,928-RPM and 100% Load, ESC2

Figure 29 are the pre-chamber pressure traces for the GEP 6.5LT engine at the 1,928-RPM power condition on the ATJ blends. The peak pressures are highest with the ATJ15 blend, with the other two ATJ blends reveal similar lower peak pre-chamber pressures.

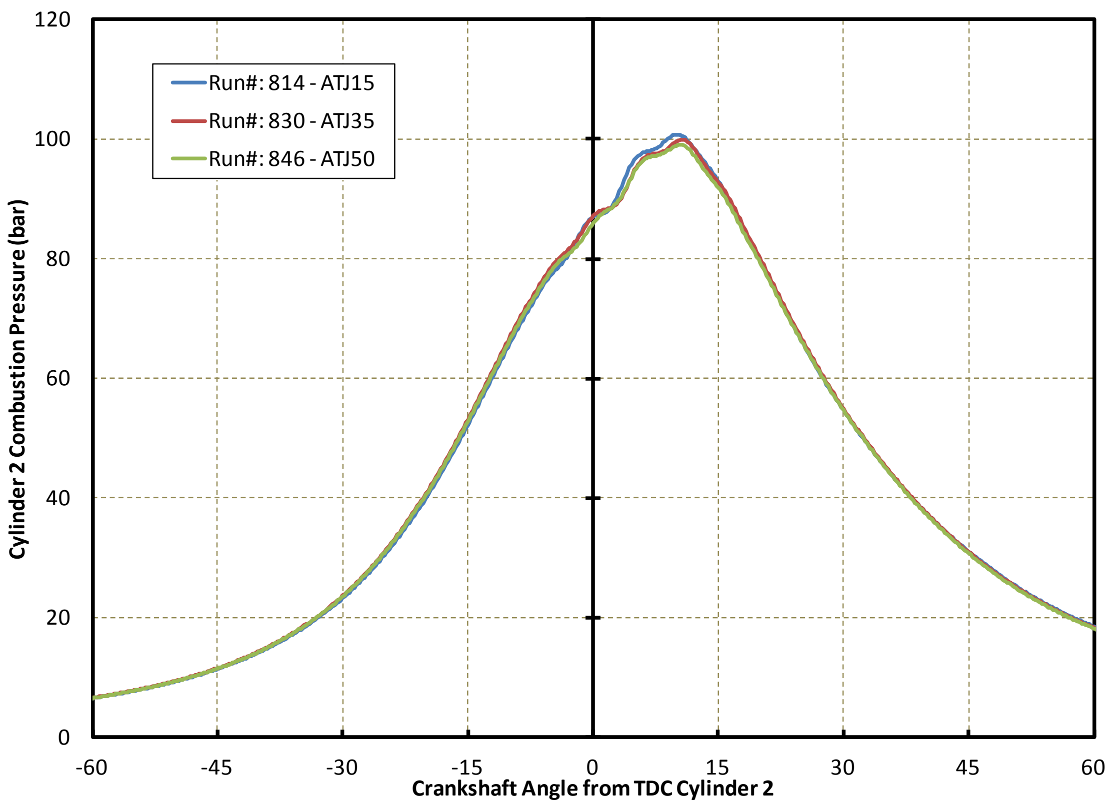


Figure 29. Pre-Chamber Pressure Histories for 1,928-RPM and 100% Load, ESC2

The apparent Heat Release Rates (HRR) calculated from the main chamber pressure traces are shown in Figure 30 for the 1,928-RPM power condition for the ATJ blends. Included in the plots are the injector needle lift that shows identical start of injection for each ATJ blend and secondary injections. There does appear to be some variation in the height of needle lift and open duration between the ATJ blends at this operating condition. The ATJ35 exhibits the highest maximum HRR. The ATJ50 blend reveals the lowest maximum HRR. The location of the maximum HRR appear to be at the same crankshaft angle with respect to TDC for the ATJ15 and ATJ50 fuels, but slightly retarded for the AJ35 fuel.

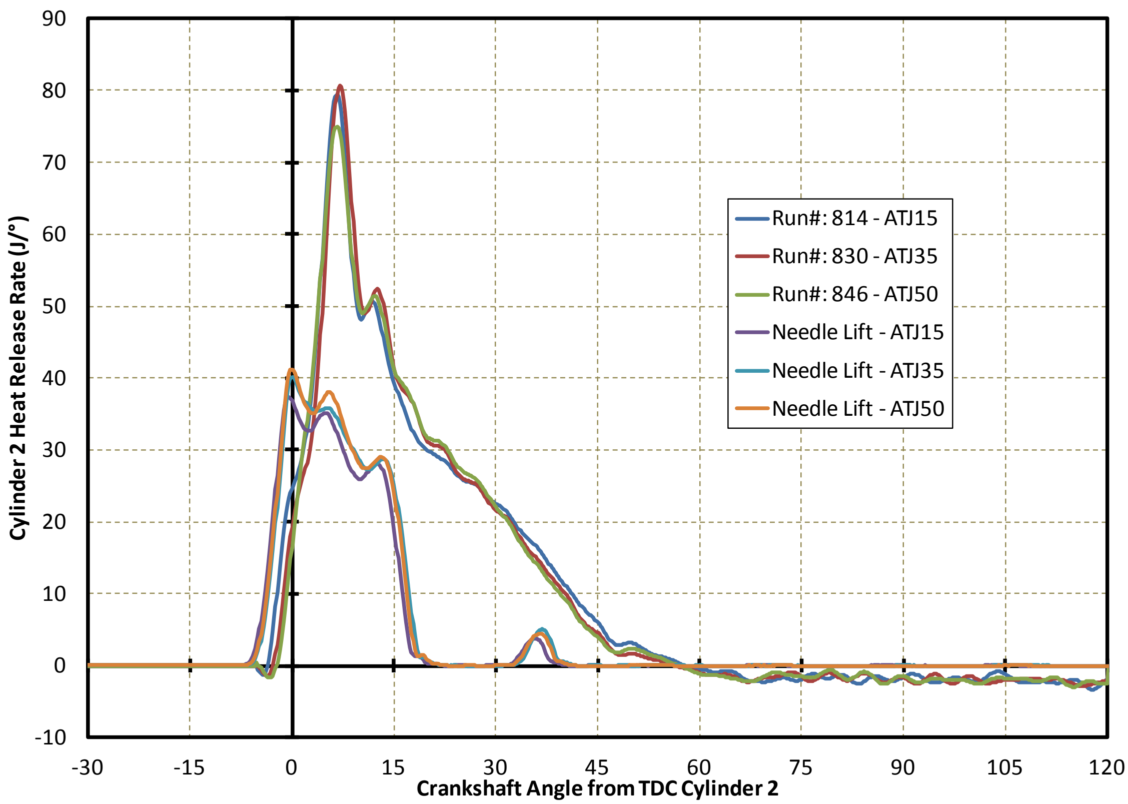


Figure 30. Heat Release Rate Histories for 1,928-RPM and 100% Load, ESC2

The fuel Mass Fraction Burned (MFB) curves are shown in Figure 31 for the 1,928-RPM power condition for each ATJ blend. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. The MFB curves are quite similar, except for the ATJ15 fuel that ignites earlier, then burns over a slightly longer overall crankshaft angle duration.

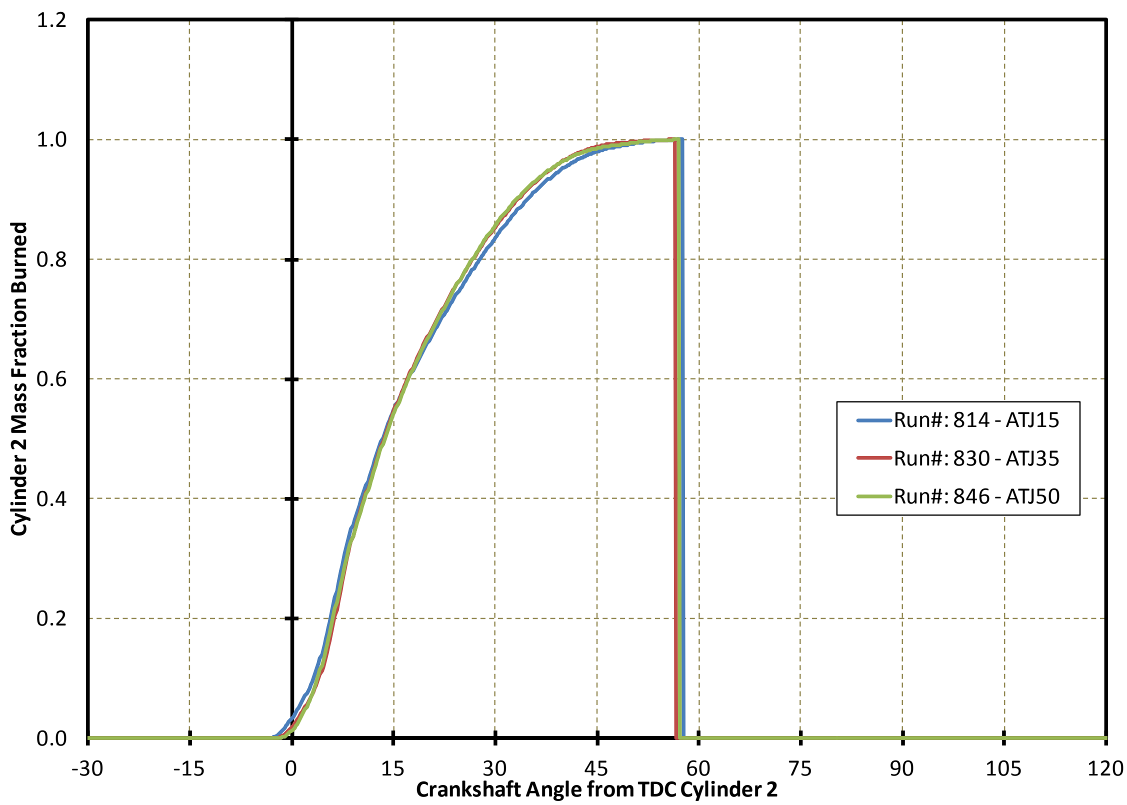


Figure 31. Fuel Mass Fraction Burned for 1,928-RPM and 100% Load, ESC2

Figure 32 are the main-chamber pressure traces for the GEP 6.5LT engine at the full load condition for the 1,500-RPM power condition on the ATJ blends. The peak pressures are similar in the main-chamber, but the ATJ35 and ATJ15 fuels appear to have a similar pressure rise rates. The ATJ50 pressure development is delayed, then rapidly increases. The ATJ blends approach constant pressure combustion near the region of peak pressure.

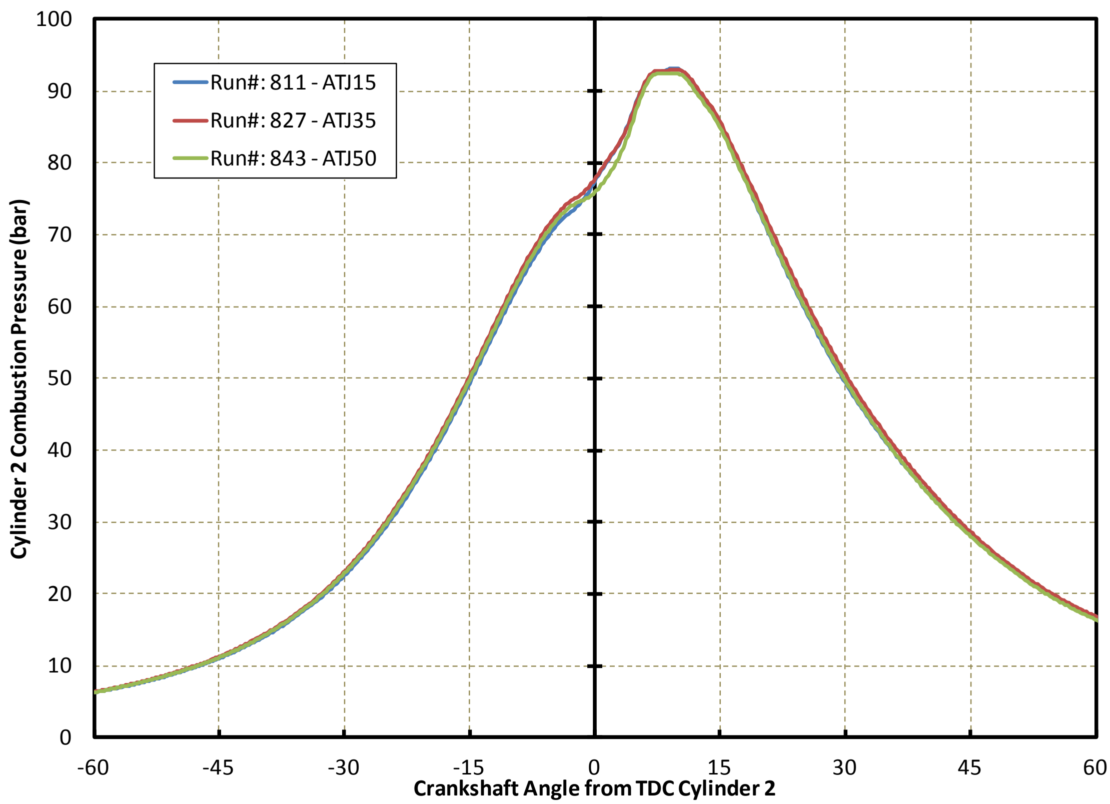


Figure 32. Main Chamber Pressure Histories for 1,500-RPM and 100% Load

Figure 33 are the pre-chamber pressure traces for the GEP 6.5LT engine at the 1,500-RPM full load power condition on the ATJ blends. The peak pressures are very similar with the three ATJ blends in the pre-chamber. Pressure rise rates in the pre-chamber also appear similar for the fuels.

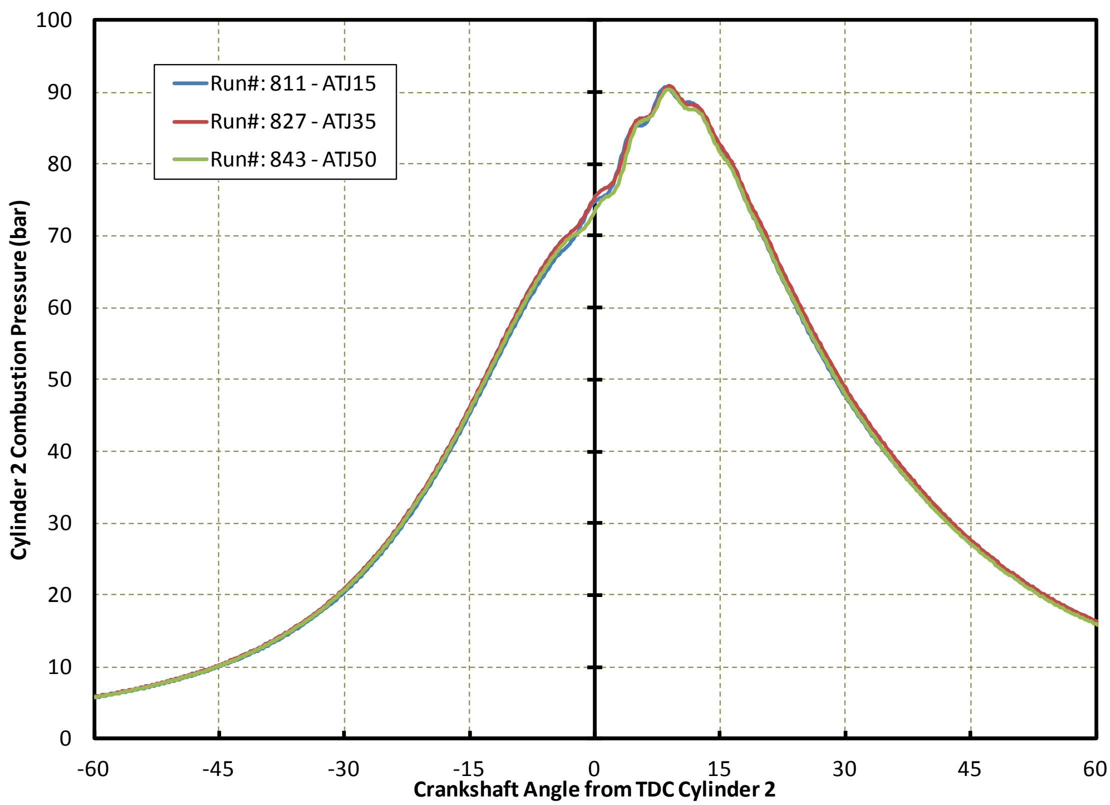


Figure 33. Pre-Chamber Pressure Histories for 1,500-RPM and 100% Load

The apparent Heat Release Rates (HRR) calculated from the main chamber pressure traces are shown in Figure 34 for the 1,500-RPM power condition for the ATJ blends. Included in the plots are the injector needle lifts that show identical start of injection for each ATJ blend. The ATJ15 and ATJ35 blends reveal similar start of combustion, slightly differing combustion rate, but nearly equal maximum HRR. The ATJ50 blend appears to ignite later then exhibit a faster burn rate, with higher maximum HRR. The location of the maximum HRR appears to be at the same crankshaft angle with respect to TDC for all three blends.

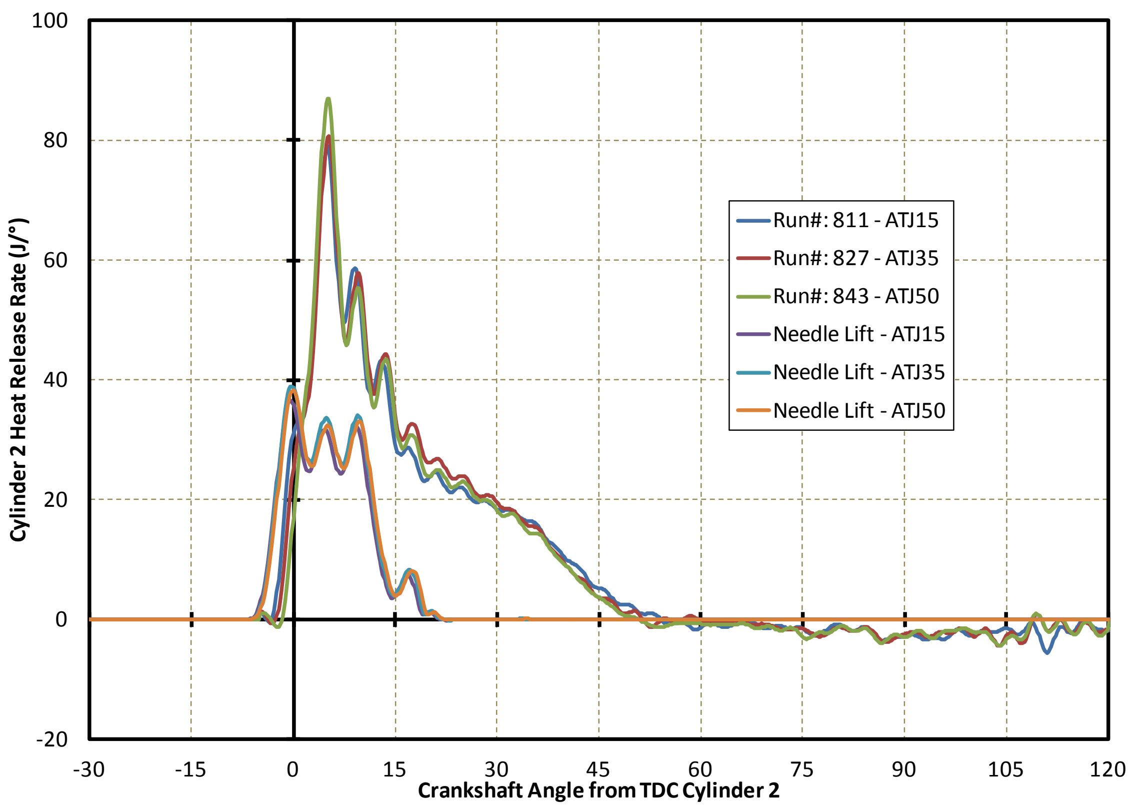


Figure 34. Heat Release Rate Histories for 1,500-RPM and 100% Load

The Mass Fraction Burned (MFB) curve is shown in Figure 35 for the 1,500-RPM power condition for each ATJ blend. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. After the initial 10% MFB, the MFB curves are very similar for all three ATJ blends up to 75% MFB, then the ATJ15 slows down and burns longer and later into the engine cycle.

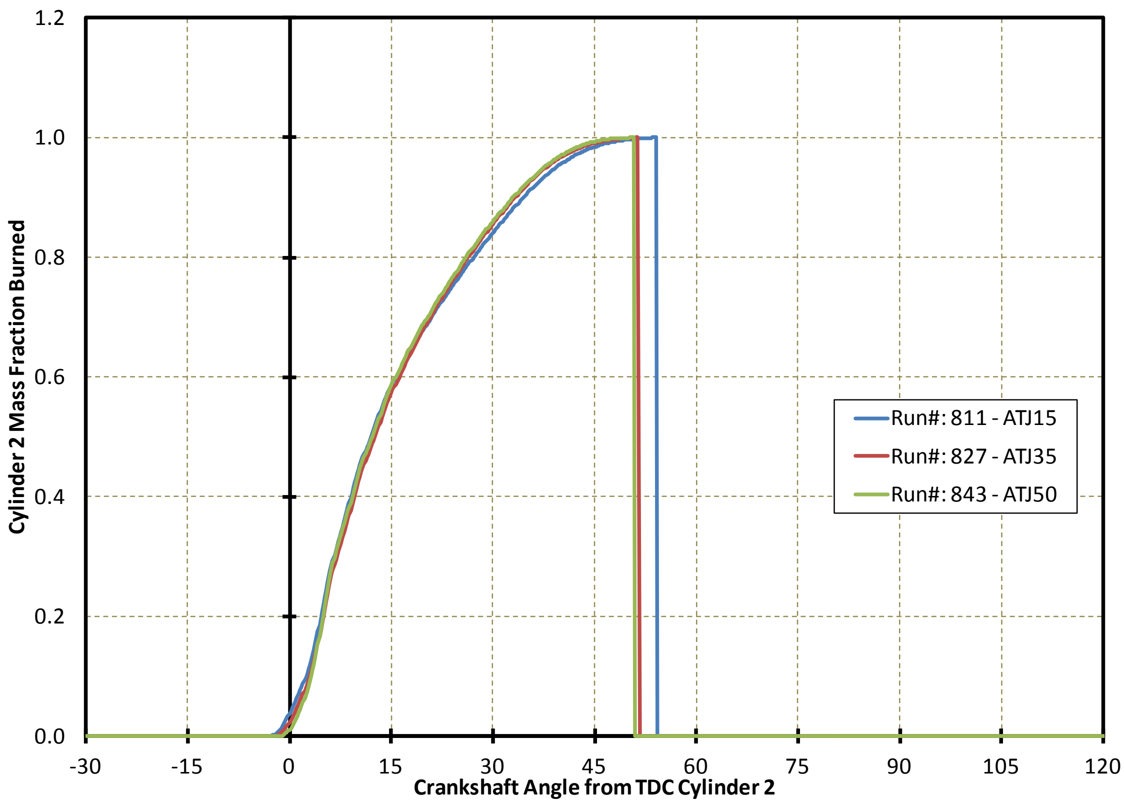


Figure 35. Fuel Mass Fraction Burned for 1,500-RPM and 100% Load

Figure 36 are the main-chamber pressure traces for the GEP 6.5LT engine at the full load condition for the 1,000-RPM power condition on the ATJ blends. The peak cylinder pressures in the main-chamber appear to increase with increasing ATJ content in the blend. The pressure rise rates seem similar for the blends.

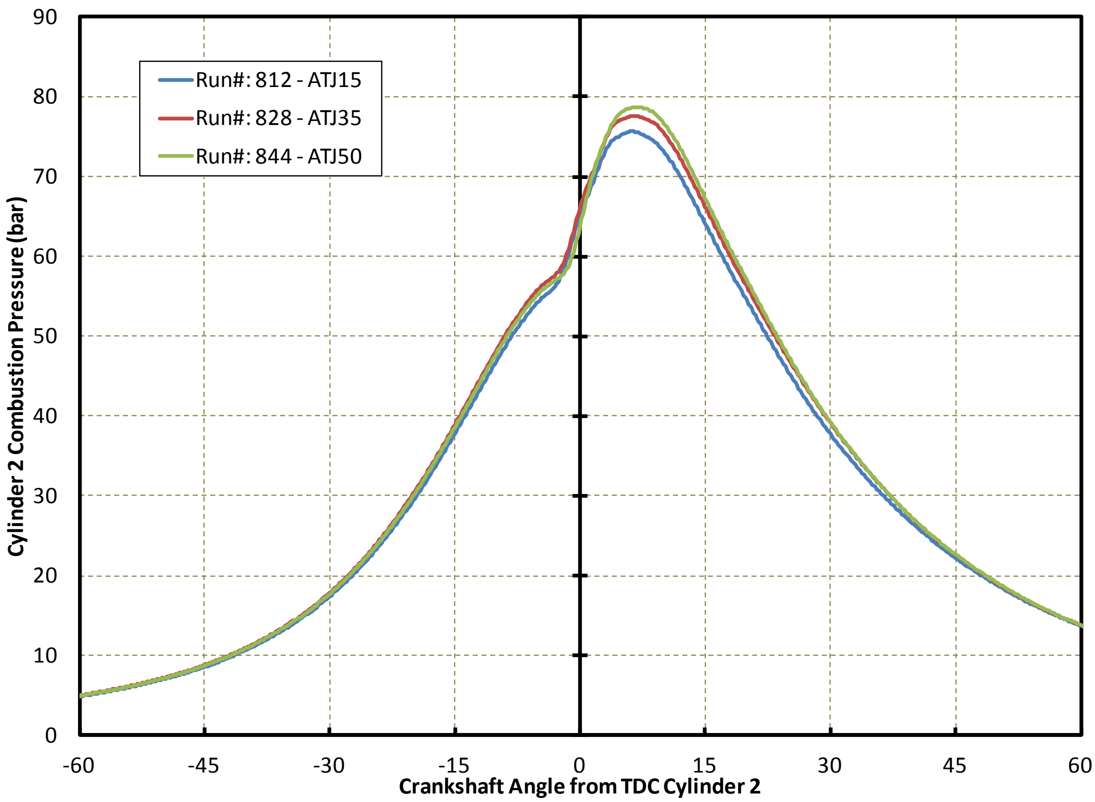


Figure 36. Main Chamber Pressure Histories for 1000-RPM and 100% Load

Figure 37 are the pre-chamber pressure traces for the GEP 6.5LT engine at the full load, 1,000-RPM, power condition on the ATJ blends. The peak pressures are higher with increased ATJ content blends in the pre-chamber. Also a heat transfer or combustion phasing difference is seen between the blends.

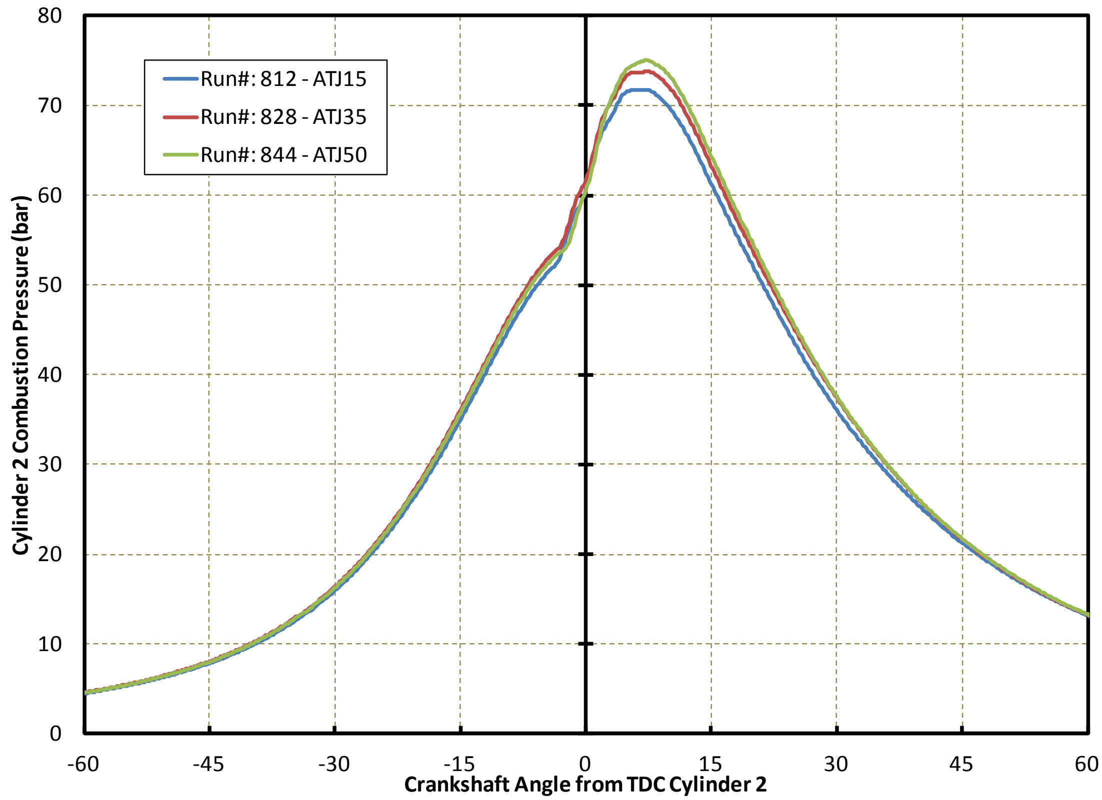


Figure 37. Pre-Chamber Pressure Histories for 1,000-RPM and 100% Load

The apparent Heat Release Rates (HRR) calculated from the main chamber pressure traces are shown in Figure 38 for the 1,000-RPM full load speed condition for the ATJ blends. Included in the plots are the injector needle lifts that show identical start of injection for each ATJ blend. All three ATJ blends exhibit rapid increases in HRR, with substantial burning evident before TDC. The ATJ35 and ATJ50 blends appear to ignite later but exhibit a faster burn rate, with the highest maximum HRR seen with the ATJ50 fuel. The location of the maximum HRR appear to be at the same crankshaft angle slightly before TDC with the ATJ15 and ATJ35 fuels, and slightly after TDC with the ATJ50 fuel.

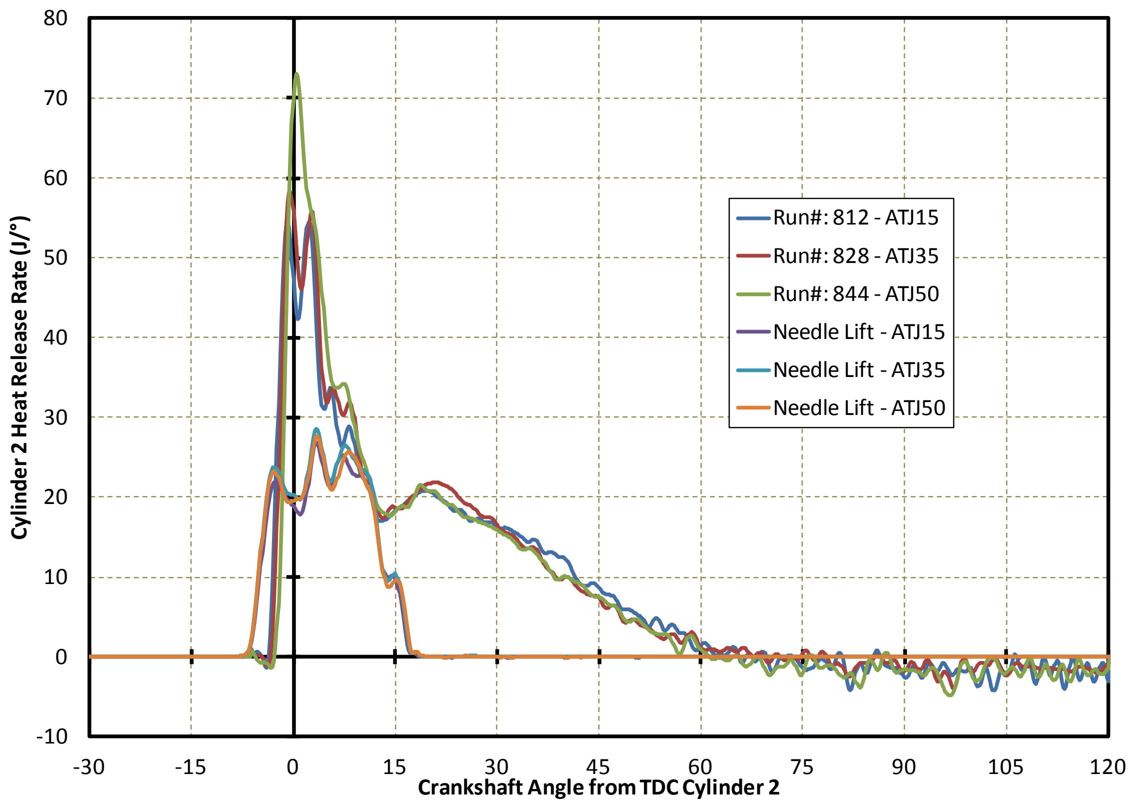


Figure 38. Heat Release Rate Histories for 1,000-RPM and 100% Load

The fuel Mass Fraction Burned (MFB) curves are shown in Figure 39 for the full load, 1,000-RPM, power condition for each ATJ blend. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. About 10% MFB is before TDC for all ATJ blends. The ATJ50 fuel burn rate speeds up from 30 to 80% MFB and has the shortest overall duration. The ATJ35 fuel has the longest combustion duration.

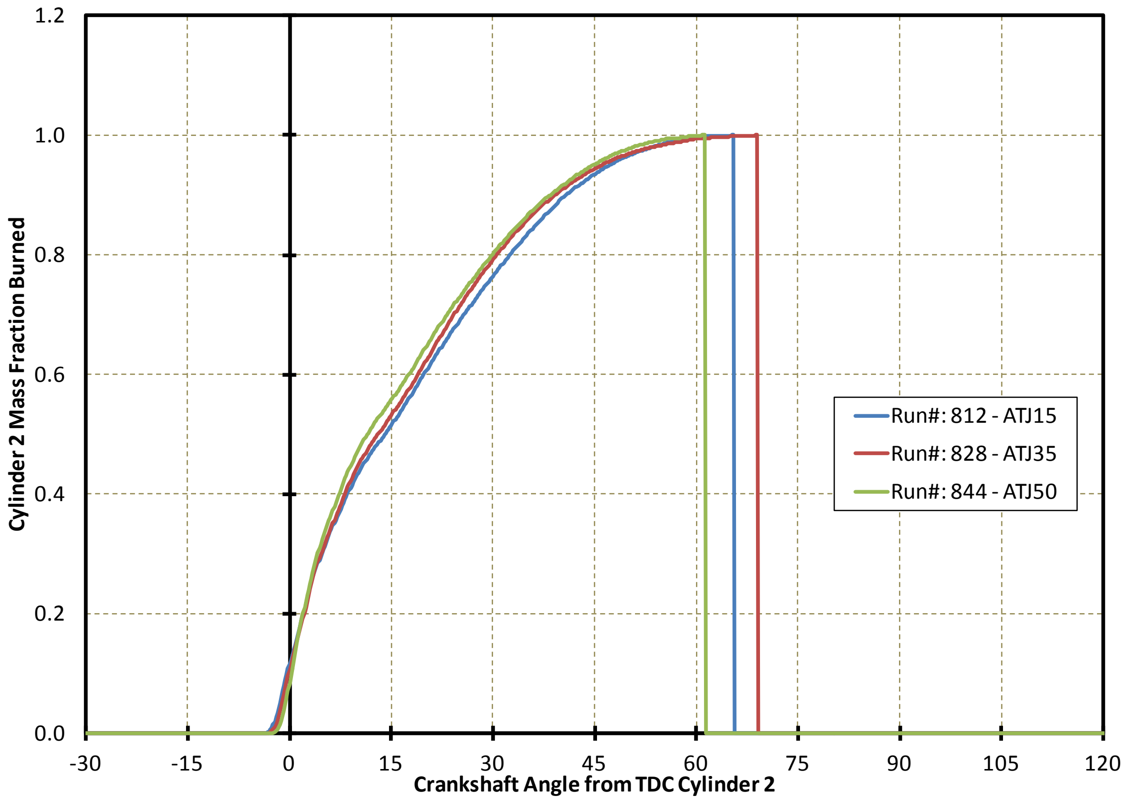


Figure 39. Fuel Mass Fraction Burned for 1,000-RPM and 100% Load

9.0 FUEL PROPERTY EFFECTS ON PERFORMANCE

A slate of 18 fuels used for the cetane window testing in the GEP 6.5LT engine, over two U.S. Army studies, had not only large variations in cetane number, but also variations in other fuel properties such as viscosity, boiling range, bulk modulus, lubricity, hydrogen/carbon atom ratio, and fuel structure type. The engine performance and combustion data was compared to the fuel property data to determine any significant fuel property variations for the GEP 6.5LT engines.

All fuel and engine performance data for peak power and the ESC were entered into a spreadsheet. A correlation worksheet function was used to calculate the correlation coefficient between measurement variables when measurements on each variable were observed for each of N subjects. The computation of the correlation coefficient is the ratio of covariation in the X and Y variable, to the individual variability in X and the individual variability in Y. Covariation is meant as the amount that X and Y vary together. So, the correlation looks at how much the two variables vary together relative to the amount they vary individually. If the covariation is large relative to the individual variability of each variable, then the relationship and the value of r is strong. The value of any correlation coefficient must be between -1 and +1 inclusive, whether large values of one variable tend to be associated with large values of the other (positive correlation), whether small values of one variable tend to be associated with large values of the other (negative correlation), or whether values of both variables tend to be unrelated (correlation near 0 (zero)).

The correlation coefficients for the fuel property variables for the test fuels are shown in Table 6 with highlighted values representing +/-0.90 or greater correlation coefficients. Some of the test fuels differed from other fuels only due to the addition of a cetane improver additive.

Fuel density is important for fuel injection, as most fuel injection systems have a fixed metering volume, thus lower density fuels could result in lower power output. The fuel density shows correlation with fuel bulk modulus, net heat of combustion, the carbon and hydrogen content, and fuel hydrocarbon type. Fuel structure has a major effect on the fuel density.

Fuel ignition quality is determined by the fuel property variables Cetane Number (CN) and Derived Cetane Number (DCN). The cetane number compares the ignition of a test fuel when bracketed by reference fuel blends in a special test engine that operates at fixed speed and injection timing, with the compression ratio altered for ignition at Top Dead Center (TDC). The DCN correlates the measured ignition delay characteristics of a fuel with the cetane number as defined by the primary reference fuels blends in a combustion bomb. It is noted CN and DCN are highly correlated, as they are both defined by reference fuel blends, but do not appear to correlate well with other fuel properties. A higher CN and DCN indicate a fuel that is more reactive, and will more readily ignite at compression ignition engine cylinder conditions of temperature and pressure at fuel injection.

Several different fuel variables are a measure of fuel structure, those being the carbon content, hydrogen content, hydrogen/carbon atom ratio (H/C), the aromatics content, olefins content, and saturates content. Table 6 suggests that H/C and saturates are highly correlated with each other, and inversely proportional to the aromatics and olefins content. The fuel Bulk Modulus (BM) is a measure of fuel compressibility, and effects fuel injection dynamics. Typically as the saturate content of a fuel increases, there are more highly branched molecule chains, the fuel is more compressible, and the bulk modulus would be lower. This fuel property data set did not show a strong correlation between BM and saturate content. The BM did correlate well with fuel density.

The test fuels boiling point data are a measure of fuel volatility; higher boiling point temperatures indicate a less volatile fuel. The distillation temperatures appear to correlate with each other and the fuel viscosity. In addition the T90-10 temperature range is an indicator of the breadth of the distillation cut that can affect engine performance and idle stability, and correlates with the T90 distillation temperature. The fuel kinematic viscosity for the fuel property set appears to correlate with the distillation data and flashpoint. The fuel flashpoint correlates with the T10 distillation temperature.

Table 6. Fuel Property Cross Correlation Table

	Density	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
Density	**1**																	
CN	-0.5320	**1**																
DCN	-0.5269	**0.9578**	**1**															
BM	**0.9301**	-0.2909	-0.3166	**1**														
Kvis	0.7097	0.0163	0.0295	0.8267	**1**													
NHofC	**-0.9724**	0.5794	0.5793	**-0.9026**	-0.6020	**1**												
C	**0.9270**	-0.5698	-0.5613	0.7968	0.5480	**-0.9126**	**1**											
H	**-0.9616**	0.6347	0.6128	-0.8563	-0.5552	**0.9824**	**-0.9423**	**1**										
H/C	**-0.9612**	0.6317	0.6101	-0.8519	-0.5557	**0.9787**	**-0.9545**	**0.9992**	**1**									
Aromatics	**0.9512**	-0.6374	-0.6323	0.8200	0.5008	**-0.9514**	0.8941	**-0.9430**	**-0.9395**	**1**								
Olefins	0.5809	-0.5600	-0.4896	0.4738	0.4895	-0.5535	0.4408	-0.5630	-0.5511	0.5716	**1**							
Saturates	**-0.9499**	0.6611	0.6464	-0.8150	-0.5266	**0.9461**	-0.8777	**0.9398**	**0.9350**	**-0.9930**	-0.6647	**1**						
Sulfur	-0.1082	-0.3762	-0.2910	-0.2781	-0.1800	0.1311	-0.0171	0.0689	0.0592	-0.0840	0.0730	0.0660	**1**					
Flash	0.8330	-0.2431	-0.2602	0.8244	0.8889	-0.7256	0.7328	-0.6926	-0.6987	0.6934	0.5724	-0.7139	-0.0268	**1**				
T10	0.8014	-0.1544	-0.1270	0.8175	**0.9465**	-0.6795	0.6893	-0.6560	-0.6621	0.6272	0.5473	-0.6500	-0.0153	**0.9644**	**1**			
T50	0.6362	0.1196	0.1273	0.8043	**0.9672**	-0.5468	0.4734	-0.4975	-0.4964	0.4131	0.3223	-0.4226	-0.1839	0.7974	0.8689	**1**		
T90	0.6594	0.0434	0.0634	0.8317	**0.9176**	-0.5976	0.5037	-0.5548	-0.5517	0.4527	0.3237	-0.4589	-0.2046	0.7167	0.8011	**0.9668**	**1**	
T90-10	0.4709	0.1457	0.1582	0.7010	0.7487	-0.4527	0.3170	-0.4063	-0.3986	0.2807	0.1460	-0.2766	-0.2753	0.4602	0.5575	0.8599	**0.9435**	**1**

9.1 GENERAL ENGINE PRODUCTS (GEP) 6.5LT ENGINE RESPONSE TO FUEL VARIABLES

9.1.1 GEP 6.5LT Emissions, Peak Power, and Idle

Data from Table 7 are the weighted average regulated gaseous emission response, peak power produced, and idle combustion mode ESC1 parameter relationships with fuel properties for the GEP 6.5LT engine. The Table 7 highlighted values represent +/-0.80 or greater correlation coefficients. The weighted average emission values use the ESC weighting factors for the calculation. The emissions data for the GEP 6.5LT engine indicate that all three regulated emission species, HC, CO, and NOx emissions responses are impacted by the fuel properties. The HC emissions decrease for the GEP 6.5LT engine with increasing values of the fuel properties KVis, flashpoint, and the T10, T50, T90 distillation temperatures. The KVis and T50 have the greatest impact on the GEP 6.5LT HC emissions. The CO emission response decreases as KVis increases, and the T50 temperatures increase, with T50 having the greatest impact. The NOx emission response increases as fuel density, BM, KVis, carbon content, and aromatics content also increase. Increasing density and aromatics content have the greatest impact for increasing NOx emissions for the GEP engine. The GEP 6.5LT weighted average NOx emission response decreases as NHofC increases, hydrogen content, H/C, and saturates contents increase. The NHofC and saturates have the greatest impact on lowering GEP 6.5LT engine weighted average NOx emissions.

The GEP 6.5LT engine Peak Power fuel property correlation data from Table 7 indicate density, BM, KVis, carbon content, aromatics, flashpoint, and T10 and T90 distillation temperatures all reveal peak power increases with fuel property value increases. Antagonistic fuel property effects on GEP 6.5LT engine power are NHofC, hydrogen content, H/C, and saturate content. The GEP 6.5LT engine has a mechanical fuel injection pump, in a Pump-Line-Nozzle (PLN) configuration. The fuel Bulk Modulus is a measure of fuel compressibility, and effects fuel injection dynamics. As the saturate content of a fuel increases, there are more highly branched molecule chains, the fuel is more compressible, and the bulk modulus would be lower. Fuel bulk modulus is anticipated to have the most impact on engines with PLN fuel injection systems, and for this fuel set it is the most significant fuel property affecting the peak power of the GEP 6.5LT engine, followed by the fuel density.

Included in Table 7 are selected combustion parameters for the ESC idle, mode 1, for the GEP 6.5LT engine. The combustion parameter peak pressure in units of bar, is indicative of the piston loadings at idle for the slate of test fuels. There exist fuel property correlations with BM, KVis, flashpoint, and T10, T50, T90 distillation temperatures for increasing the GEP 6.5LT cylinder pressure at idle with increasing fuel property values. The Location of Peak Pressure (LPP) with respect to engine TDC has impacts on engine efficiency and idle roughness. Fuel property correlations do not exist for LPP timing at idle for the GEP 6.5LT engine.

The parameter Maximum Heat Release Rate (MHRR) in Joules/° from Table 7 indicate the level of premixed combustion that has been associated with knock, piston shock loading, and increased NOx emissions. At an idle mode the combustion in the engine is barely overcoming friction to keep the engine running, the heat release rate effects are muted. At the GEP 6.5LT engine idle mode there is not any correlation of fuel properties with MHRR. The combustion parameter 50 Percent Mass Fraction Burned Angle (50MFB) attempts to condense the engine heat release profile curve into a single quantitative value. It is the angle with respect to engine TDC at which 50-percent of the energy released by the combustion event has occurred. Combustion closer to TDC should result in greater engine efficiency.

9.1.2 GEP 6.5LT Engine ESC A-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50%, and 25%) at three engine speeds. The three engine speeds are calculated based on a formula that takes into consideration the power and the speed at the rated condition. For the GEP 6.5LT engine the ESC A-Speed of 1,928 rpm is close to the peak torque speed of 2,100 rpm, as the torque curve in the 1,900-2,100 rpm speed range is fairly flat. Mode 2 is 100%, Mode 6 is 75%, Mode 5 is 50%, and Mode 7 is 25% loads respectively at 1,928-RPM.

Table 7. Fuel Property effects on GEP 6.5LT Weighted Average Emissions, Peak Power, and Mode 1 Combustion

			Weighted Average Emissions, Peak Power, and Idle Combustion - Fuel Property Correlation Coefficients for GEP 6.5LT Engine																	
	Units	*Engine Condition*	*Density*	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
HC	*gr/hp-hr*	*13-Mode Weighted Average*	-0.7165	-0.0659	-0.0520	-0.7978	**-0.8575**	0.6266	-0.6695	0.6115	0.6210	-0.5398	-0.2532	0.5280	0.0895	**-0.8029**	**-0.8533**	**-0.8656**	**-0.8282**	-0.6763
CO	*gr/hp-hr*	*13-Mode Weighted Average*	-0.5187	-0.3646	-0.2847	-0.6933	**-0.8203**	0.4136	-0.4392	0.3508	0.3603	-0.3155	-0.0735	0.2979	0.3259	-0.7194	-0.7522	**-0.8304**	-0.7622	-0.6408
NOx	*gr/hp-hr*	*13-Mode Weighted Average*	**0.9396**	-0.6966	-0.6906	**0.8063**	0.5539	**-0.9155**	**0.8676**	**-0.9131**	**-0.9100**	**0.9550**	0.6129	**-0.9579**	0.0447	0.7310	0.6844	0.4578	0.4713	0.2747
Power	*BHP*	*Rated*	**0.9621**	-0.3758	-0.3533	**0.9634**	**0.8225**	**-0.9229**	**0.8733**	**-0.9128**	**-0.9125**	**0.8544**	0.5283	**-0.8542**	-0.1643	**0.8393**	**0.8545**	0.7836	**0.8161**	0.6589
Mode 1 Peak Pressure	*bar*	*IDLE, 800-RPM*	0.7610	-0.2299	-0.2071	**0.8017**	**0.9217**	-0.6607	0.6802	-0.6528	-0.6591	0.5861	0.5092	-0.6071	0.0549	**0.8732**	**0.9174**	**0.8880**	**0.8569**	0.6807
Mode 1 Location of Peak Pressure	*°ATDC*	*IDLE, 800-RPM*	-0.2347	0.0595	0.1037	-0.3203	-0.4244	0.1423	-0.2892	0.1844	0.2023	-0.0176	0.0283	0.0120	-0.1756	-0.4015	-0.4214	-0.4596	-0.4731	-0.4229
Mode 1 Maximun Heat Release Rate	*J/°*	*IDLE, 800-RPM*	0.3821	-0.6365	-0.5561	0.2193	0.3155	-0.3137	0.3909	-0.3264	-0.3348	0.3713	0.5991	-0.4245	0.6289	0.5069	0.4670	0.1832	0.1502	-0.0502
Mode 1 50 Percent Mass Fraction Burn Angle	*°ATDC*	*IDLE, 800-RPM*	-0.2798	-0.2846	-0.2575	-0.4581	-0.7604	0.1485	-0.2848	0.1714	0.1891	0.0335	0.0006	-0.0293	-0.0382	-0.5906	-0.6916	**-0.8481**	**-0.8236**	-0.7373

The A-Speed combustion correlations with fuel properties are shown in Table 8 for the GEP 6.5LT engine. The Table 8 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 2 peak cylinder pressures shows increasing cylinder pressure with increasing values of fuel density, BM, and T90. The peak pressure reveals a reduction with increases in NHofC, hydrogen content, and H/C. The fuel BM showed the most significant fuel property effect on peak pressure. The Mode 2 LPP advances towards TDC with increasing BM. The GEP 6.5LT engine has a PLN fuel injection system that is sensitive to BM effects, thus combustion advances as BM increases. There are not any fuel properties that show a significant relationship to either the MHRR or 50MFB angle for Mode 2 for the GEP 6.5LT engine. ESC Mode 2 is one of the points on the full load power curve.

Mode 6 (75% load), Table 8, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density and bulk modulus. Peak cylinder pressures are reduced with increasing values of NHofC and hydrogen content for the GEP 6.5LT engine. The fuel BM showed the most significant fuel property effect on peak cylinder pressure. There are not any fuel properties that show a significant relationship to either the LPP or the MHRR at Mode 6 for the GEP 6.5LT engine. The location of the 50MFB advanced due to fuel density and BM increases for Mode 6.

Mode 5 (50% load), Table 8, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density and BM. Peak cylinder pressure at Mode 5 decreases with increasing values of NHofC, hydrogen content, and H/C atom ratio. The engine combustion response for the LPP, the MHRR, and the 50MFB angle with the GEP 6.5LT engine do not reveal any significant fuel property correlations at Mode 5.

Mode 7 (25% load), Table 8, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, and aromatics content. Peak cylinder pressure at Mode 5 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. For Mode 7 the engine combustion response for LPP, the MHRR, and the 50MFB angle with the GEP 6.5LT engine do not reveal any significant fuel property correlations.

For the ESC A-Speed with the GEP 6.5LT engine, the combustion parameter peak pressure was impacted mostly by fuel density, BM, NHofC, and fuel structure at all A-Speed load conditions. The fuel bulk modulus was the single fuel property that had the greatest impact for the A-Speed combustion performance of the GEP 6.5LT engine.

9.1.3 GEP 6.5LT Engine ESC B-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50%, and 25%) at three engine speeds. For the GEP 6.5LT engine the ESC B-Speed of 2,641 rpm represents an intermediate speed between peak torque and peak power. Mode 8 is 100%, Mode 4 is 75%, Mode 3 is 50%, and Mode 9 is 25% loads respectively.

The B-Speed combustion correlations with fuel properties are shown in Table 9 for the GEP 6.5LT engine. The Table 9 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 8 peak cylinder pressures shows increasing cylinder pressure with increases values of fuel density, BM, KVis, carbon content, aromatics, flashpoint, and T10 and T90 distillation temperatures. The peak pressure reveals a reduction with increases in NHofC, hydrogen content, H/C, and saturates content. The fuel density showed the most significant fuel property effect on peak pressure, followed by fuel BM. There were not any fuel properties that show a significant relationship to the LPP, the MHRR, or the 50MFB angle for Mode 8 operation of the GEP 6.5LT engine. ESC Mode 8 is one of the points along the full load power curve.

Mode 4 (75% load), Table 9, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, and aromatics content. Peak cylinder pressures are reduced with increasing values of NHofC, and saturate content for the GEP 6.5LT engine. The fuel density followed by the saturate content showed the most significant fuel property effects on peak cylinder pressure. There are not any fuel properties that show a significant relationship to the LPP. The Mode 4 MHRR for the GEP 6.5LT engine reveals an increase in MHRR with decreasing cetane number. The location of 50MFB did not reveal any significant relationship with fuel properties for Mode 4.

Table 8. GEP 6.5LT European Stationary Cycle A-Speed fuel property effects on Modal Combustion Variables

			European Stationary Cycle A Speed (1928-RPM) Modal Combustion Fuel Property Correlation Coefficients for GEP 6.5LT Engine																	
	Units	*Engine Condition*	*Density*	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
Mode 2 Peak Pressure	*bar*	*100% LOAD*	**0.8239**	-0.2893	-0.3189	**0.9029**	0.7551	**-0.8204**	0.7716	**-0.8185**	**-0.8195**	0.6584	0.3641	-0.6520	-0.1917	0.7288	0.7294	0.7740	**0.8037**	0.7109
Mode 2 Location of Peak Pressure	*°ATDC*		-0.7067	0.0145	0.1122	**-0.8645**	-0.7371	0.7020	-0.5711	0.6320	0.6272	-0.5496	-0.1858	0.5272	0.3595	-0.6993	-0.6692	-0.7777	-0.7808	-0.7126
Mode 2 Maximun Heat Release Rate	*J/°*		0.4962	-0.5156	-0.5224	0.3519	0.2017	-0.5020	0.6575	-0.5981	-0.6120	0.4925	0.4204	-0.5091	0.0412	0.4060	0.3261	0.1263	0.1121	-0.0251
Mode 2 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.6131	0.2515	0.4173	-0.6636	-0.4459	0.5912	-0.5661	0.5358	0.5376	-0.6031	-0.2670	0.5877	0.2903	-0.6019	-0.4805	-0.3834	-0.3521	-0.2223
Mode 6 Peak Pressure	*bar*	*75% LOAD*	**0.8183**	-0.4920	-0.5388	**0.8671**	0.6549	**-0.8292**	0.7176	**-0.8026**	-0.7968	0.7049	0.4524	-0.7071	-0.0676	0.6606	0.6362	0.6459	0.6796	0.5903
Mode 6 Location of Peak Pressure	*°ATDC*		-0.5170	-0.0194	0.1359	-0.6567	-0.5950	0.4823	-0.3563	0.3792	0.3742	-0.3883	-0.1242	0.3715	0.2220	-0.6413	-0.5361	-0.6179	-0.5526	-0.4696
Mode 6 Maximun Heat Release Rate	*J/°*		0.2390	-0.7214	-0.6222	0.0102	-0.1508	-0.3022	0.3229	-0.3926	-0.3931	0.3087	0.3650	-0.3337	0.7021	0.0356	0.0380	-0.1926	-0.1319	-0.2039
Mode 6 50 Percent Mass Fraction Burn Angle	*°ATDC*		**-0.8116**	0.5402	0.6352	**-0.8018**	-0.5626	0.7978	-0.6901	0.7603	0.7543	-0.7648	-0.4521	0.7616	0.0078	-0.7436	-0.6365	-0.5186	-0.5112	-0.3566
Mode 5 Peak Pressure	*bar*	*50% LOAD*	**0.8539**	-0.5884	-0.5772	**0.8340**	0.6188	**-0.8740**	0.7180	**-0.8545**	**-0.8426**	0.7823	0.5834	-0.7964	-0.1067	0.6409	0.6313	0.5820	0.6108	0.4978
Mode 5 Location of Peak Pressure	*°ATDC*		-0.5444	-0.0324	0.0989	-0.6109	-0.6170	0.4515	-0.4629	0.4016	0.4079	-0.3881	-0.1373	0.3732	0.2523	-0.7438	-0.6617	-0.5763	-0.4454	-0.2515
Mode 5 Maximun Heat Release Rate	*J/°*		-0.0683	-0.2451	-0.1883	-0.1548	-0.4596	-0.0371	-0.0306	-0.0632	-0.0548	0.0739	-0.4111	-0.0080	0.2626	-0.4611	-0.4209	-0.3252	-0.1828	-0.0206
Mode 5 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.7764	0.5858	0.6420	-0.7052	-0.5004	0.7491	-0.5968	0.7222	0.7090	-0.7560	-0.5773	0.7716	-0.0182	-0.6961	-0.6003	-0.4312	-0.4002	-0.2227
Mode 7 Peak Pressure	*bar*	*25% LOAD*	**0.8804**	-0.5858	-0.6248	**0.8233**	0.6361	**-0.8392**	0.7890	**-0.8118**	**-0.8100**	**0.8282**	0.5753	**-0.8371**	-0.0698	0.7668	0.7121	0.5376	0.5197	0.3266
Mode 7 Location of Peak Pressure	*°ATDC*		0.5454	-0.6705	-0.5255	0.3133	0.2325	-0.5320	0.6030	-0.6120	-0.6176	0.5693	0.4912	-0.5892	0.4561	0.4064	0.4166	0.1622	0.1842	0.0249
Mode 7 Maximun Heat Release Rate	*J/°*		0.4384	-0.7749	-0.6239	0.2593	0.1157	-0.4631	0.3671	-0.5005	-0.4876	0.5344	0.6203	-0.5760	0.3457	0.1637	0.1961	0.0442	0.1358	0.0799
Mode 7 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.0095	-0.3551	-0.1809	-0.0749	-0.2068	-0.1024	-0.0207	-0.1376	-0.1223	0.0973	0.1805	-0.1146	0.0381	-0.3716	-0.2741	-0.1712	-0.0021	0.1489

Mode 3 (50% load), Table 9, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density and aromatics content. Peak cylinder pressure at Mode 3 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. The engine combustion responses for LPP and the MHRR with the GEP 6.5LT engine do not reveal any significant fuel property correlations at Mode 3. The location of 50MFB advanced due to fuel density, BM, and aromatics content increases. The 50MFB angle retarded from TDC when NHofC, hydrogen content, H/C, and saturates content increased at Mode 3. The fuel density, followed by NHofC, then saturates, were the most significant fuel properties affecting the 50MFB angle at Mode 3.

Mode 9 (25% load), Table 9, peak cylinder pressure does not reveal any significant fuel property relationships. The Mode 9 combustion response for LPP, MHRR, or 50MFB with the GEP 6.5LT engine did not reveal any significant fuel property correlations.

For the ESC B-Speed with the GEP 6.5LT engine, the combustion parameter peak pressure was impacted mostly by fuel density, fuel BM, NHofC, and fuel structure at all B-Speed load conditions. The fuel density, fuel BM, and fuel structure were the fuel properties that had the greatest impact on the B-Speed combustion performance for the GEP 6.5LT engine.

9.1.4 GEP 6.5LT Engine ESC C-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50%, and 25%) at three engine speeds. For the GEP 6.5LT engine the ESC C-Speed of 2,995 rpm is close to the rated power speed of 3,400 rpm. Mode 10, Mode 12, Mode 13, and Mode 11 are the 100%, 75%, 50%, and 25% loads respectively.

Table 9. GEP 6.5LT European Stationary Cycle B-Speed fuel property effects on Modal Combustion Variables

	Units	Engine Condition	Density	CN	DCN	BM	Kvis	NHofC	C	H	H/C	Aromatics	Olefins	Saturates	Sulfur	Flash	T10	T50	T90	T90-10
			European Stationary Cycle B Speed (2641-RPM) Modal Combustion - Fuel Property Correlation Coefficients for GEP 6.5LT Engine																	
Mode 8 Peak Pressure	bar	100% LOAD	**0.9300**	-0.4580	-0.4181	**0.9239**	**0.8157**	**-0.8835**	**0.8239**	**-0.8756**	**-0.8736**	**0.8161**	0.5405	**-0.8210**	-0.0063	**0.8290**	**0.8449**	0.7897	**0.8151**	0.6628
Mode 8 Location of Peak Pressure	°ATDC		0.4463	-0.7122	-0.5596	0.2718	0.1948	-0.4192	0.4116	-0.4710	-0.4679	0.4950	0.4919	-0.5216	0.5516	0.3502	0.3659	0.1348	0.1561	0.0139
Mode 8 Maximun Heat Release Rate	J/°		0.4977	-0.7434	-0.6157	0.3196	0.0664	-0.5668	0.4460	-0.5991	-0.5845	0.6264	0.5229	-0.6458	0.1963	0.1226	0.1383	0.0289	0.1497	0.1311
Mode 8 50 Percent Mass Fraction Burn Angle	°ATDC		-0.4185	0.7364	0.7250	-0.1860	-0.0105	0.3809	-0.4632	0.4048	0.4114	-0.5372	-0.3827	0.5443	-0.4388	-0.3188	-0.2236	0.1221	0.1255	0.2978
Mode 4 Peak Pressure	bar	75% LOAD	**0.8672**	-0.6360	-0.6317	**0.8027**	0.6310	**-0.8160**	0.7299	-0.7978	-0.7917	**0.8159**	0.5813	**-0.8268**	0.0574	0.7214	0.6982	0.5526	0.5746	0.4104
Mode 4 Location of Peak Pressure	°ATDC		0.6110	-0.4500	-0.4566	0.5363	0.4247	-0.5017	0.6178	-0.5592	-0.5660	0.5941	0.3934	-0.5977	-0.0615	0.5796	0.5186	0.3418	0.2848	0.1080
Mode 4 Maximun Heat Release Rate	J/°		0.5251	**-0.8320**	-0.7024	0.3228	0.0741	-0.5874	0.4866	-0.6271	-0.6149	0.6372	0.5439	-0.6587	0.2433	0.1703	0.1767	0.0187	0.1300	0.0824
Mode 4 50 Percent Mass Fraction Burn Angle	°ATDC		-0.7846	0.7603	0.7557	-0.6430	-0.4535	0.7434	-0.7099	0.7426	0.7413	-0.7835	-0.5625	0.7945	-0.3356	-0.6883	-0.6125	-0.3587	-0.3607	-0.1612
Mode 3 Peak Pressure	bar	50% LOAD	**0.8602**	-0.7323	-0.6916	0.7726	0.5920	**-0.8544**	0.7535	**-0.8540**	**-0.8473**	**0.8024**	0.6390	**-0.8228**	0.1867	0.7007	0.6794	0.5277	0.5582	0.3981
Mode 3 Location of Peak Pressure	°ATDC		0.1616	0.0067	-0.0307	0.1717	0.0323	-0.1476	0.0845	-0.1004	-0.0960	0.1369	-0.2499	-0.0886	-0.2192	0.0139	0.0562	0.0532	0.0825	0.0833
Mode 3 Maximun Heat Release Rate	J/°		0.5246	-0.7838	-0.6607	0.3553	0.0916	-0.6131	0.4634	-0.6282	-0.6128	0.6338	0.5576	-0.6575	0.1727	0.1622	0.1615	0.0460	0.1752	0.1536
Mode 3 50 Percent Mass Fraction Burn Angle	°ATDC		**-0.8970**	0.6459	0.6160	**-0.8065**	-0.6519	**0.8793**	-0.7516	**0.8654**	**0.8566**	**-0.8502**	-0.7068	**0.8760**	-0.1418	-0.7777	-0.7558	-0.5727	-0.5923	-0.4031
Mode 9 Peak Pressure	bar	25% LOAD	0.7834	-0.7474	-0.7130	0.6738	0.5450	-0.7347	0.7059	-0.7462	-0.7440	0.7357	0.6253	-0.7600	0.1645	0.6649	0.6398	0.4457	0.4528	0.2739
Mode 9 Location of Peak Pressure	°ATDC		-0.3426	-0.0428	0.0472	-0.3557	-0.4968	0.2200	-0.3681	0.2137	0.2330	-0.1563	-0.0434	0.1486	-0.1708	-0.6242	-0.6042	-0.4368	-0.2916	-0.0699
Mode 9 Maximun Heat Release Rate	J/°		0.6351	-0.7998	-0.6738	0.4708	0.3138	-0.6400	0.5546	-0.6614	-0.6509	0.7000	0.7043	-0.7389	0.2126	0.4137	0.4066	0.2196	0.2790	0.1618
Mode 9 50 Percent Mass Fraction Burn Angle	°ATDC		-0.6426	0.4566	0.4781	-0.5536	-0.5897	0.5375	-0.6128	0.5454	0.5562	-0.5187	-0.4657	0.5395	-0.3886	-0.7881	-0.7516	-0.4839	-0.4023	-0.1420

The C-Speed combustion correlations with fuel properties are shown in Table 10 for the GEP 6.5LT engine. The Table 10 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 10 peak cylinder pressure shows increasing cylinder pressure with increases values of fuel density and bulk modulus. The peak pressure reveals a reduction with increases in NHofC, hydrogen content, and H/C. The fuel BM showed the most significant fuel property effect on peak pressure. There are not any fuel properties that show a significant relationship to either the LPP or the MHRR for Mode 10 with the GEP 6.5LT engine. The 50MFB angle advances towards TDC with aromatics content increases. The 50MFB retards from TDC with increases in saturates content. ESC Mode 10 is also included as one of the points on the full load power curve.

Mode 12 (75% load), Table 10, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, and aromatics content. Peak cylinder pressures are reduced with increasing values of NHofC, hydrogen content, H/C, and saturate content for the GEP 6.5LT engine. The fuel density and NHofC showed the most significant fuel property effects on peak cylinder pressure. The Mode 12 LPP did not show any significant fuel property correlation. The MHRR at Mode 12 decreases with an increasing CN for the GEP 6.5LT engine. The location of 50MFB advances towards TDC due to fuel density, BM, carbon content, and aromatics content increases. The 50MFB angle retards away from TDC when NHofC, hydrogen content, H/C, and saturate contents increase for Mode 12. Fuel density had the most impact on the 50MFB angle.

Mode 13 (75% load), Table 10, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, carbon content, and aromatics content. Peak cylinder pressures are reduced with increasing values of NHofC, hydrogen content, H/C, and saturate content for the GEP 6.5LT engine. The NHofC and fuel density showed the most significant fuel property effects on peak cylinder pressure. There are not any fuel properties that show a significant relationship to the LPP. The MHRR at Mode 13 decreases with a CN increase for the GEP 6.5LT engine. The location of 50MFB advances towards TDC due to fuel density, BM, and aromatics content increases. The 50MFB angle retards away from TDC when NHofC, hydrogen

content, H/C, and saturate contents increase for Mode 13. Fuel density had the most impact on the 50MFB angle.

Mode 11 (25% load), Table 10 peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, C, and aromatics content. Peak cylinder pressure at Mode 11 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. Fuel density was the most significant property effecting peak pressure. The Mode 11 combustion response for LPP with the GEP 6.5LT engine does not reveal any significant fuel property correlations. The Mode 11 MHRR for the GEP 6.5LT engine reveals a decrease in MHRR when cetane number increases. The location of 50MFB advanced towards TDC due to flashpoint and T10 distillation temperature increases for Mode 11.

For the ESC C-Speed with the GEP 6.5LT engine, the combustion parameter peak pressure was impacted mostly by fuel density, fuel BM, NHofC, and fuel structure at all C-Speed load conditions. The fuel density, NHofC, BM were the fuel properties that had the greatest impact on the C-Speed combustion performance for the GEP 6.5LT engine. The cetane number did impact combustion performance at the intermediate to light loads for the ESC C-Speeds.

Table 10. GEP 6.5LT European Stationary Cycle C-Speed fuel property effects on Modal Combustion Variables

			European Stationary Cycle C Speed (2995-RPM) Modal Combustion - Fuel Property Correlation Coefficients for GEP 6.5LT Engine																	
	Units	*Engine Condition*	*Density*	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
Mode 10 Peak Pressure	*bar*	*100% LOAD*	**0.8568**	-0.4966	-0.4456	**0.8638**	0.7158	**-0.8536**	0.7419	**-0.8592**	**-0.8516**	0.7408	0.5308	-0.7511	-0.1153	0.6601	0.6997	0.7104	0.7861	0.7029
Mode 10 Location of Peak Pressure	*°ATDC*		-0.2306	0.3682	0.2283	-0.1436	-0.2421	0.2452	-0.1985	0.2668	0.2602	-0.2808	-0.6575	0.3505	-0.1842	-0.1857	-0.2138	-0.1763	-0.2425	-0.2180
Mode 10 Maximun Heat Release Rate	*J/°*		0.5191	-0.7762	-0.6288	0.3425	0.1906	-0.5514	0.4230	-0.5792	-0.5640	0.6084	0.6720	-0.6509	0.2627	0.2413	0.2691	0.1139	0.2035	0.1333
Mode 10 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.7957	0.6745	0.6485	-0.6684	-0.5232	0.7376	-0.6782	0.7196	0.7148	**-0.8223**	-0.6329	**0.8400**	-0.1523	-0.7166	-0.6691	-0.3983	-0.3799	-0.1565
Mode 12 Peak Pressure	*bar*	*75% LOAD*	**0.9081**	-0.6312	-0.6130	**0.8554**	0.6536	**-0.9026**	0.7850	**-0.8890**	**-0.8800**	**0.8725**	0.6502	**-0.8883**	-0.0804	0.6920	0.6899	0.5931	0.6533	0.5241
Mode 12 Location of Peak Pressure	*°ATDC*		-0.6516	0.0304	0.1488	-0.7184	-0.6689	0.5546	-0.6103	0.5156	0.5258	-0.5051	-0.1130	0.4762	0.3346	-0.7669	-0.7074	-0.6305	-0.5361	-0.3519
Mode 12 Maximun Heat Release Rate	*J/°*		0.6196	**-0.8194**	-0.7028	0.4438	0.2314	-0.6544	0.5448	-0.6642	-0.6526	0.7135	0.6305	-0.7406	0.2415	0.3344	0.3291	0.1533	0.2425	0.1542
Mode 12 50 Percent Mass Fraction Burn Angle	*°ATDC*		**-0.9101**	0.6173	0.6397	**-0.8320**	-0.6662	**0.8764**	**-0.8245**	**0.8738**	**0.8721**	**-0.8530**	-0.5923	**0.8621**	-0.0678	-0.7969	-0.7680	-0.5963	-0.6170	-0.4306
Mode 13 Peak Pressure	*bar*	*50% LOAD*	**0.9239**	-0.6586	-0.6303	**0.8539**	0.6419	**-0.9175**	**0.8325**	**-0.9217**	**-0.9154**	**0.8827**	0.6247	**-0.8938**	-0.0509	0.7117	0.6938	0.5901	0.6371	0.4996
Mode 13 Location of Peak Pressure	*°ATDC*		-0.4133	-0.1930	-0.0379	-0.5132	-0.5323	0.3220	-0.4163	0.2901	0.3045	-0.2453	-0.0190	0.2261	0.3020	-0.6343	-0.5563	-0.5050	-0.3996	-0.2462
Mode 13 Maximun Heat Release Rate	*J/°*		0.5695	**-0.8371**	-0.7004	0.3790	0.1842	-0.6010	0.5176	-0.6330	-0.6226	0.6633	0.6083	-0.6916	0.3119	0.2910	0.2895	0.1146	0.1968	0.1127
Mode 13 50 Percent Mass Fraction Burn Angle	*°ATDC*		**-0.8856**	0.6350	0.5941	**-0.8039**	-0.6908	**0.8455**	-0.7870	**0.8511**	**0.8470**	**-0.8403**	-0.6641	**0.8609**	-0.0766	-0.7695	-0.7630	-0.6218	-0.6384	-0.4630
Mode 11 Peak Pressure	*bar*	*25% LOAD*	**0.9274**	-0.6459	-0.6365	**0.8640**	0.6844	**-0.8925**	**0.8234**	**-0.8831**	**-0.8784**	**0.8922**	0.6604	**-0.9076**	-0.0181	0.7961	0.7547	0.6068	0.6276	0.4526
Mode 11 Location of Peak Pressure	*°ATDC*		-0.3437	-0.2707	-0.0819	-0.4665	-0.4857	0.2553	-0.3385	0.2105	0.2239	-0.1967	0.0620	0.1702	0.3492	-0.5798	-0.4951	-0.4640	-0.3494	-0.2105
Mode 11 Maximun Heat Release Rate	*J/°*		0.6631	**-0.8537**	-0.7396	0.4783	0.2877	-0.6714	0.6052	-0.6983	-0.6899	0.7378	0.6683	-0.7681	0.2362	0.4295	0.4037	0.1937	0.2533	0.1279
Mode 11 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.7991	0.3118	0.3982	-0.7842	-0.7358	0.7120	-0.7371	0.6992	0.7052	-0.6787	-0.4307	0.6801	0.0929	**-0.8851**	**-0.8228**	-0.6627	-0.5808	-0.3501

9.2 ENGINE AND FUEL PROPERTY COMBUSTION SUMMARY

At the European Stationary Cycle A-Speed the GEP 6.5LT engine displayed impacts from fuel properties on combustion performance. The fuel properties density, BM, net heat of combustion, and fuel H/C atom ratio all effected peak cylinder pressures, at all loads, with the GEP 6.5LT engine. Combustion phasing was not impacted by fuel properties for the GEP 6.5LT engine.

For the European Stationary Cycle B-Speed the GEP 6.5LT engine had significant impacts from fuel properties on combustion performance. The fuel properties density, BM, KVis, net heat of combustion, fuel H/C, and fuel structure all effected peak cylinder pressures, at all but the lightest load, with the GEP 6.5LT engine. Combustion phasing at intermediate loads were impacted by the same fuel properties for the GEP 6.5LT engine.

At the European Stationary Cycle C-Speed the GEP 6.5LT engine also displayed some significant impacts from fuel properties on combustion performance. The fuel properties density, BM, net heat of combustion, and fuel H/C atom ratio all effected peak cylinder pressures, at all loads, with the GEP 6.5LT engine. Combustion phasing at intermediate loads were affected by the same fuel properties for the GEP 6.5LT engine. The combustion rate for the GEP 6.5LT engine was sensitive to cetane number at intermediate and light loads.

10.0 SUMMARY

A GEP 6.5LT engine was operated on three ATJ/JP-8 blends and evaluated for power, performance, and emissions over the 13-modes European Stationary Cycle and a full-load power curve. The three ATJ/JP-8 blends included 15%, 35% and 50% ATJ content with 44.2, 36.4 and 32.0 cetane numbers respectively. There was very little impact on power and performance with the ATJ fuel blends. Engine exhaust HC and CO emissions increased with increasing ATJ content in the blends. The engine Filter Smoke Number decreased with increasing ATJ content in the blends. The engine out NOx emissions were highest with the ATJ35 blend and lowest with the ATJ50 blend.

The combustion and fuel data from this testing was included into a data set from prior cetane window testing for the GEP 6.5LT engine [1]. The results from the ATJ testing data did not significantly alter the fuel property and performances correlations previously seen. Cetane number effects on combustion appeared to be especially important at high speeds and light to intermediate loads. Prior observations with the GEP 6.5LT engine included:

- TFLRF staff was able to observe that fuels with low cetane number may be detrimental to IDI engines at high loads due to excessive HRR (1.5 to 2 times higher). This excessive combustion noise may, in the long run, damage engine internal components. Generally speaking, low cetane number fuel will provide a hard-to-start condition when the engine and environment are cold.
- Traditionally high cetane fuels operating on engines with static timing promotes NOx formation. This phenomenon was seen on the GEP 6.5LT engine. High cetane number can also cause rough engine operation at light load conditions due to higher MFB before TDC.
- It is recommended that the cetane number for ground vehicles stay between 40 and 60. It is also recommend that bulk modulus stay above 180,000 psi for engines with pump-line-nozzle type fuel injection systems. Finally it is recommended that a fuel's distillation characteristics exhibit a T90-T10 temperature that is greater than 50 °C.
- When engine power output is the primary design goal for a fuel, density is the primary property of interest; the higher the better.

11.0 REFERENCE

1. Hansen, Yost, & Frame, "Tactical/Combat Engines Cetane Window Evaluation," Interim Report No. 436, U.S. Army TARDEC Fuels and Lubricants Research Facility, Southwest Research Institute, San Antonio, TX, January 2013, ADA587315.

APPENDIX A.

GEP 6.5LT European Stationary Cycle Combustion Diagrams

The following combustion indicator diagrams are for each of the 13-modes of the European Stationary Cycle. Modes 2, 8, and 10 were included in the discussions related to the full-load pwer curves. The plots in Figure A-1 through Figure A-52 include four plots for each of the 13-modes. These four plots include the engine main chamber pressure, the engine pre-chamber pressures, the Heat Release Rate with needle lift, and the Mass Fraction Burned curve for each of the ATJ15, ATJ35, and ATJ50 fuels. Modes of interest that showed a strong cetane number influence on combustion are Mode 4, Mode 11, Mode 12, and Mode 13.

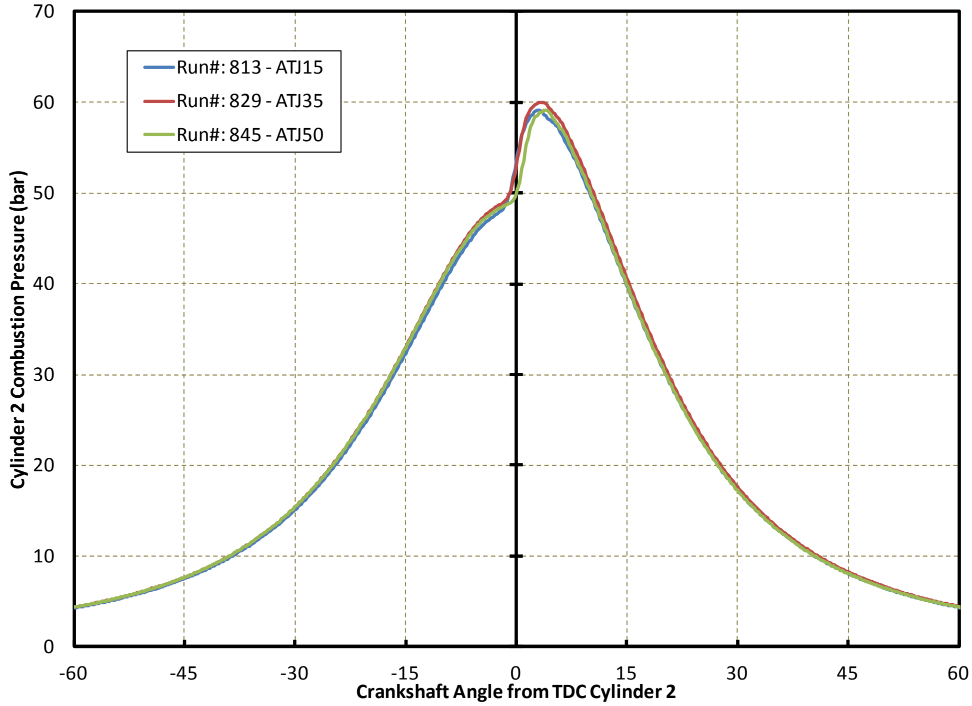


Figure A-1. Main Chamber Pressure Histories for 750-RPM and 0% Load, ESC1

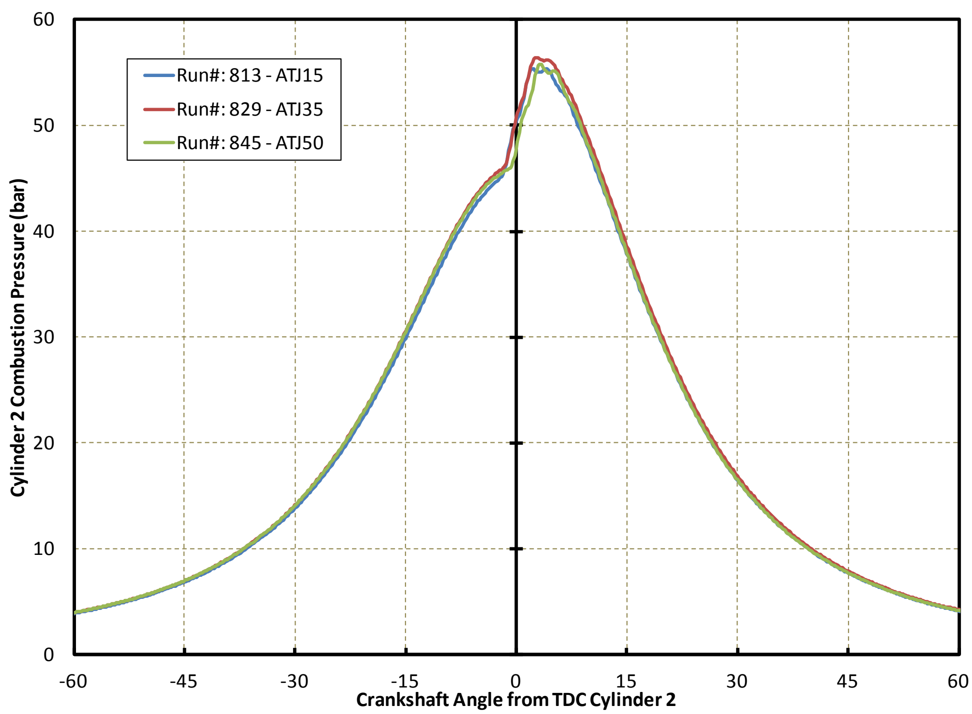


Figure A-2. Pre-Chamber Pressure Histories for 750-RPM and 0% Load, ESC1

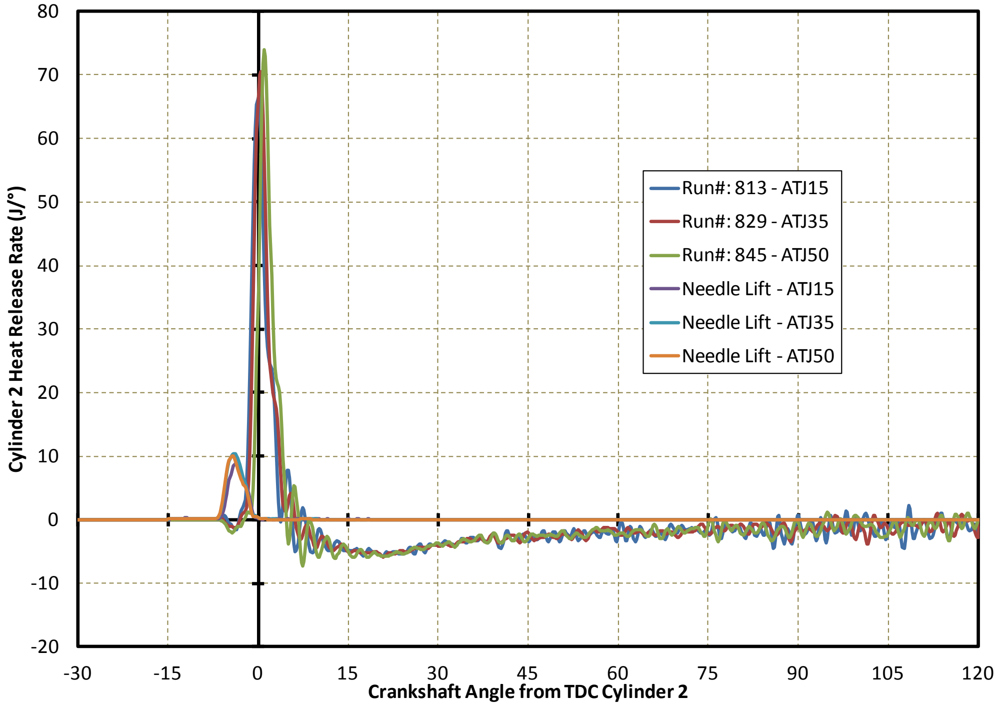


Figure A-3. Heat Release Rate Histories for 750-RPM and 0% Load, ESC1

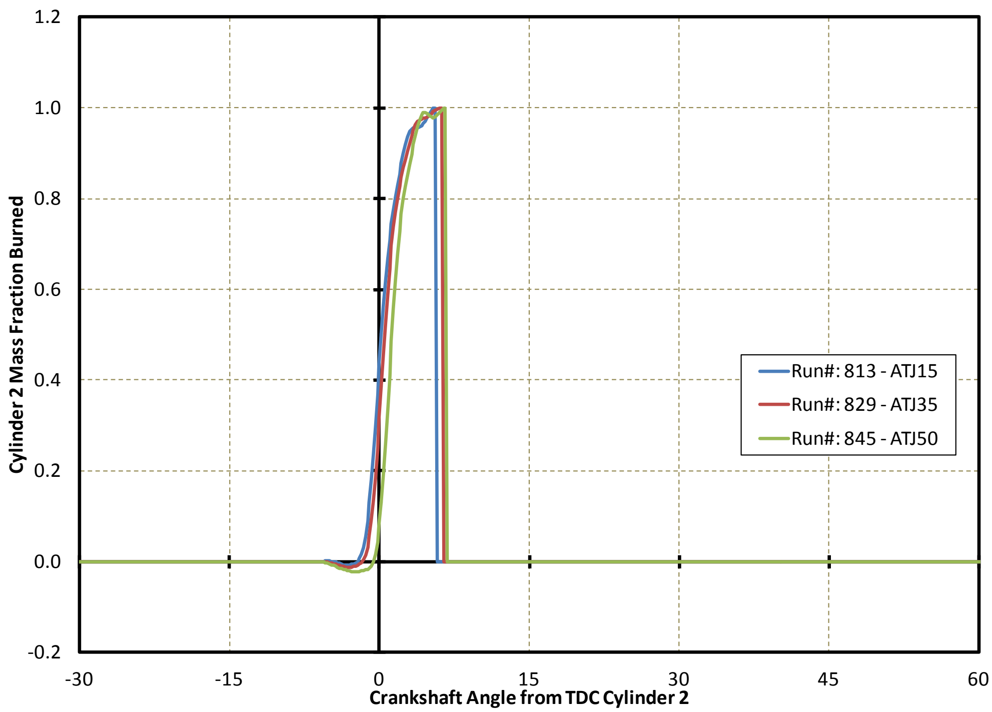


Figure A-4. Fuel Mass Fraction Burned for 750-RPM and 0% Load, ESC1

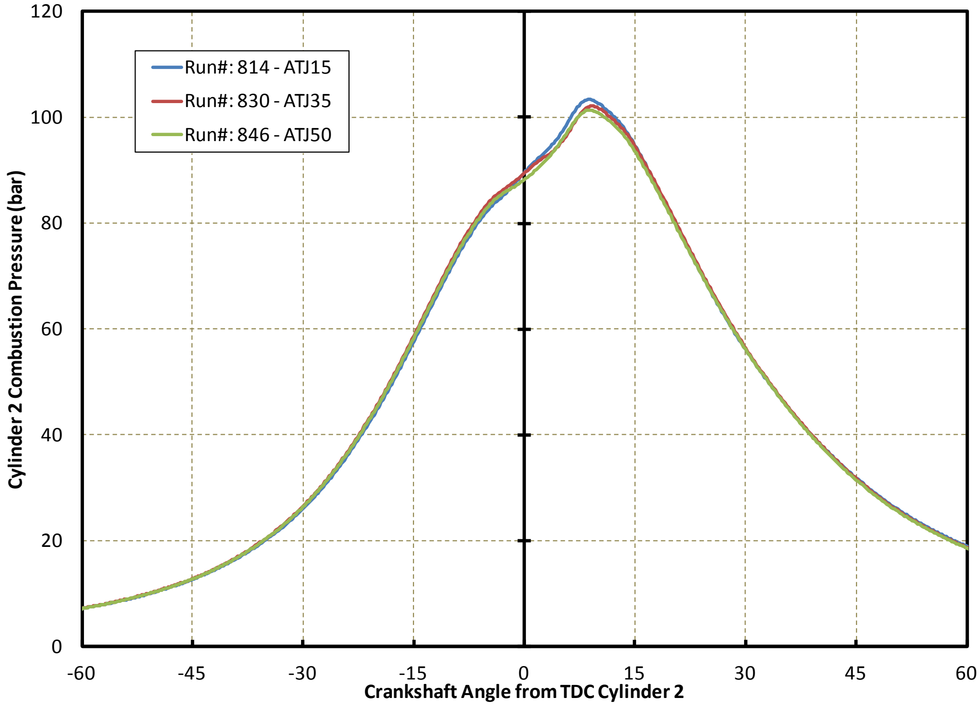


Figure A-5. Main Chamber Pressure Histories for 1,928-RPM and 100% Load, ESC2

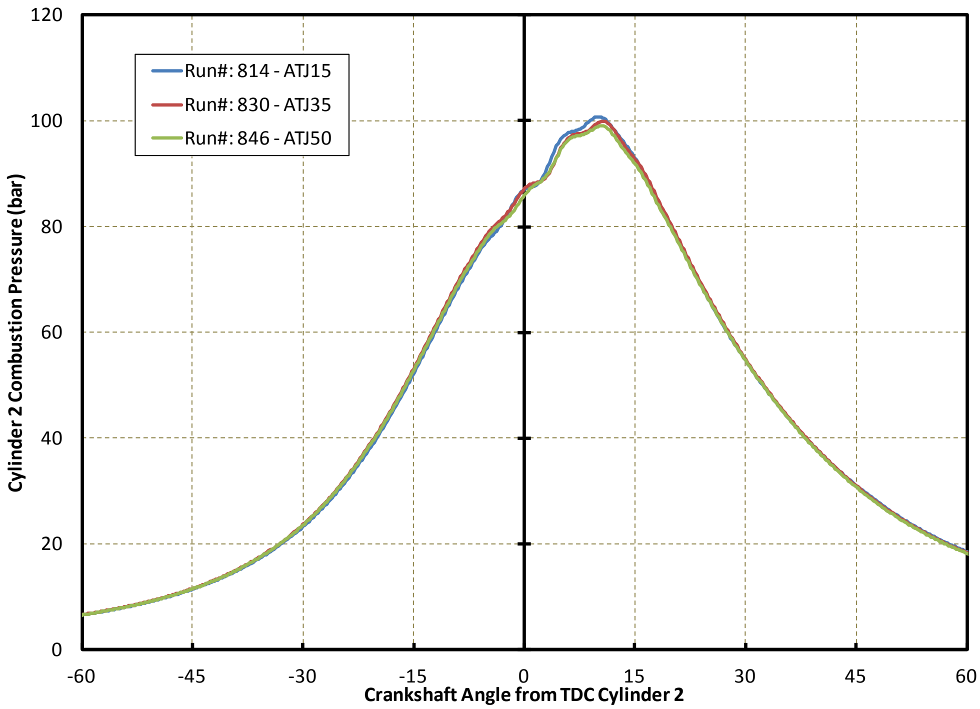


Figure A-6. Pre-Chamber Pressure Histories for 1,928-RPM and 100% Load, ESC2

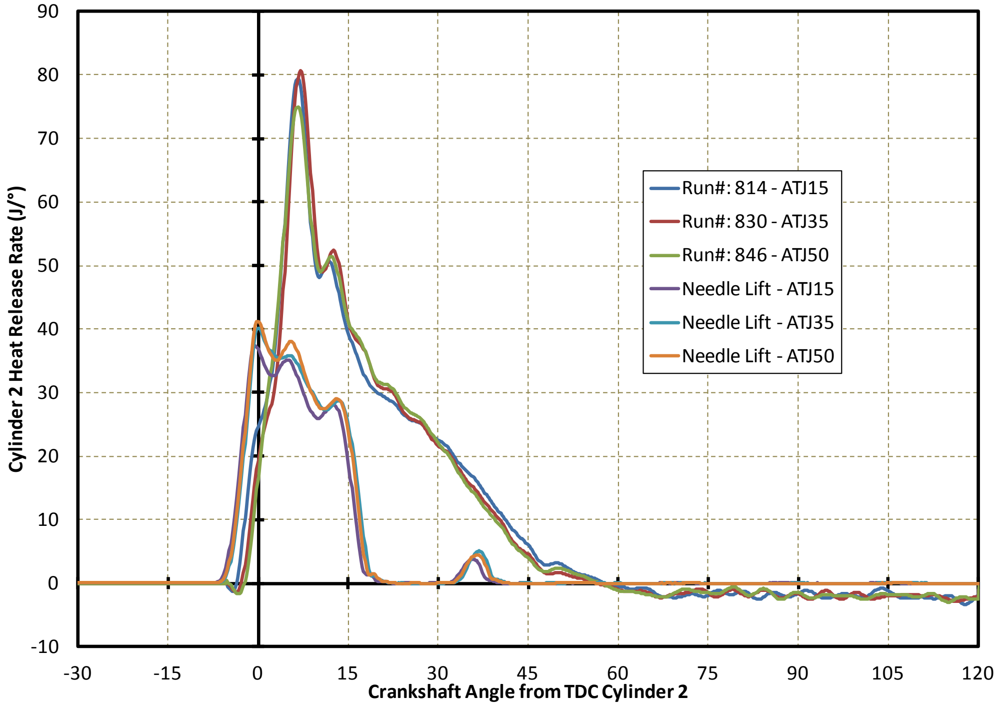


Figure A-7. Heat Release Rate Histories for 1,928-RPM and 100% Load, ESC2

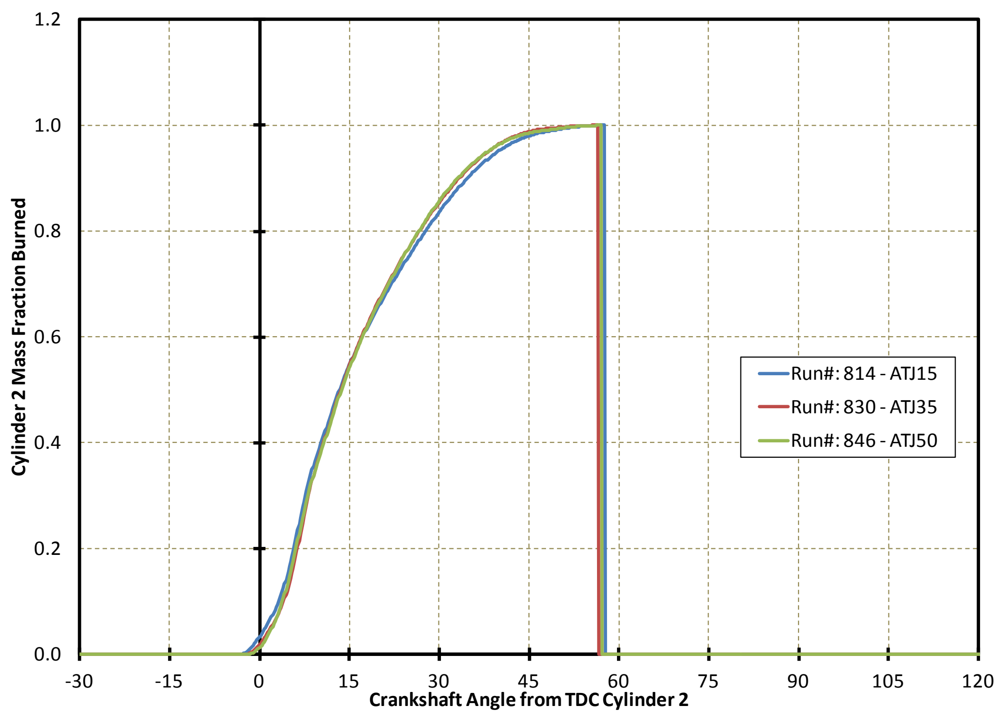


Figure A-8. Fuel Mass Fraction Burned for 1,928-RPM and 100% Load, ESC2

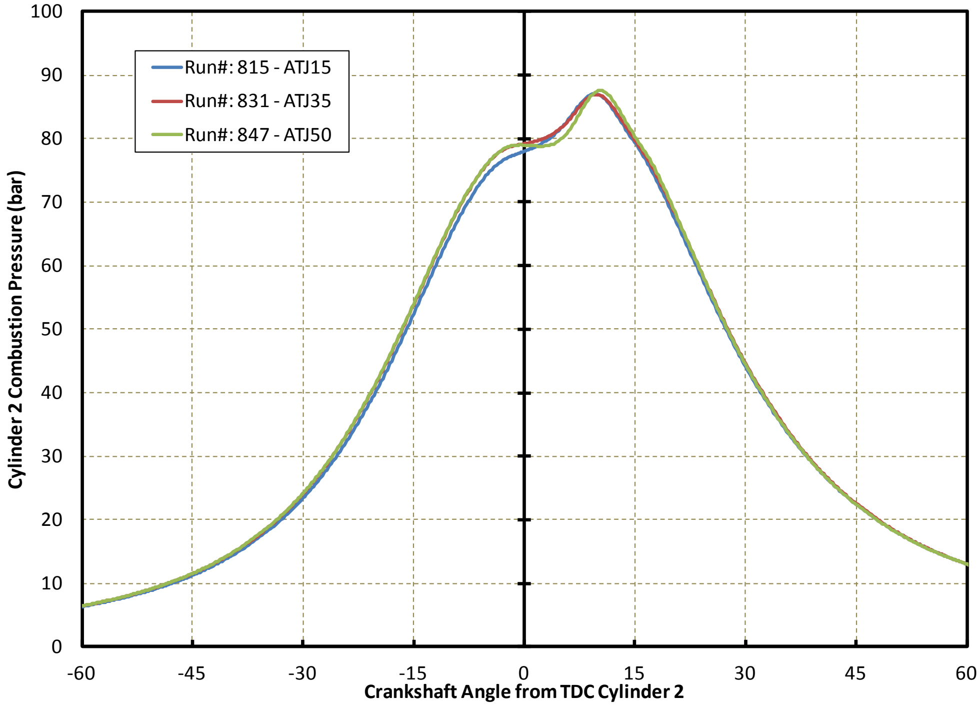


Figure A-9. Main Chamber Pressure Histories for 2,641-RPM and 50% Load, ESC3

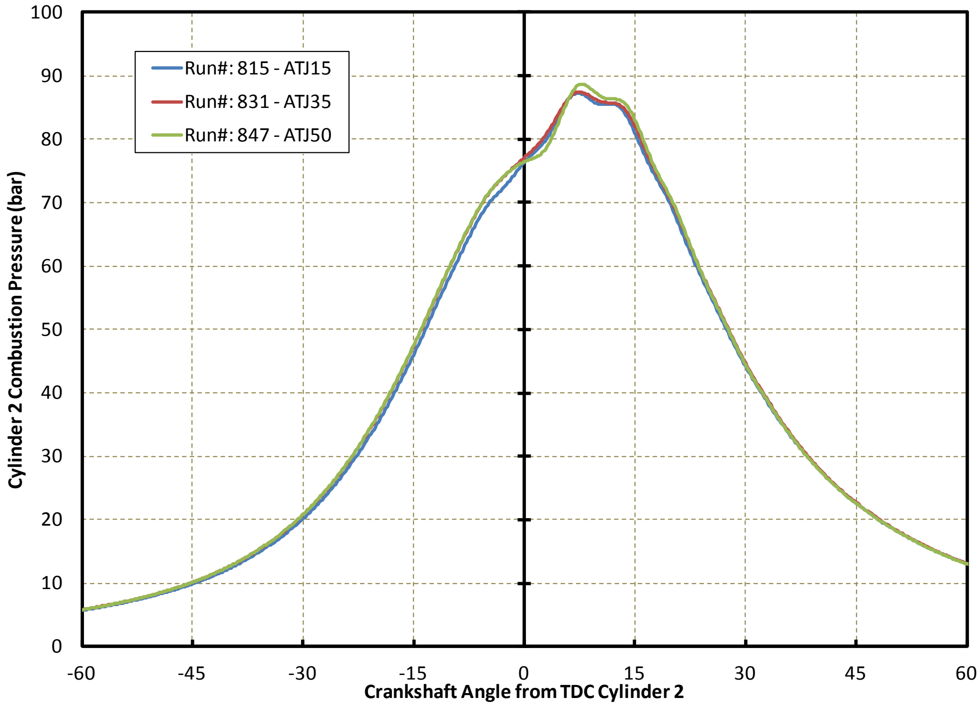


Figure A-10. Pre-Chamber Pressure Histories for 2,641-RPM and 50% Load, ESC3

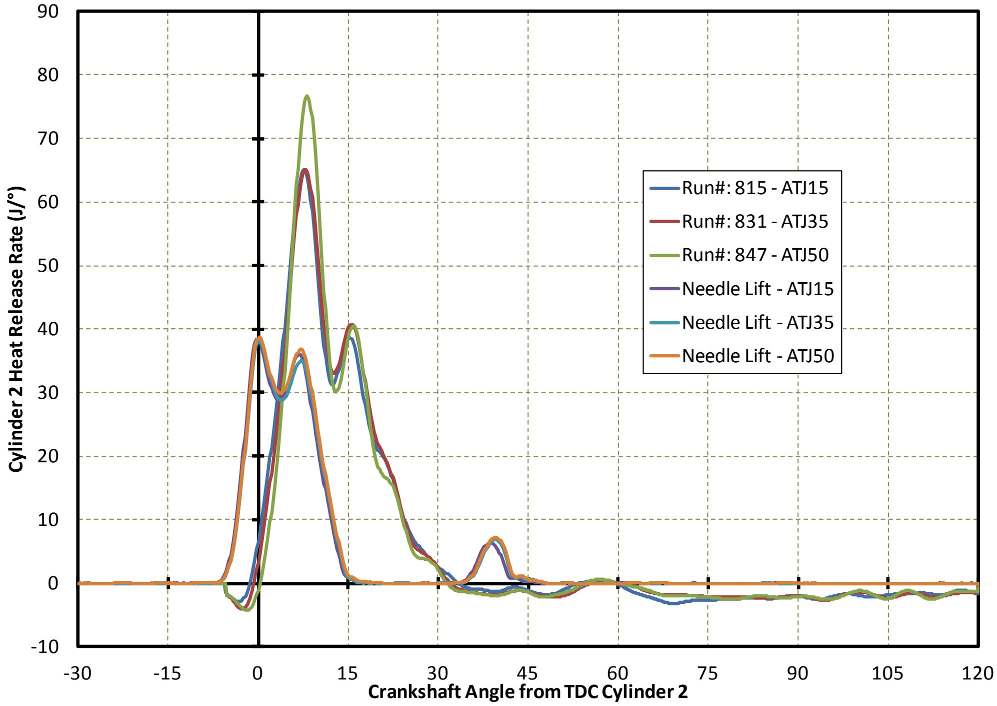


Figure A-11. Heat Release Rate Histories for 2,641-RPM and 50% Load, ESC 3

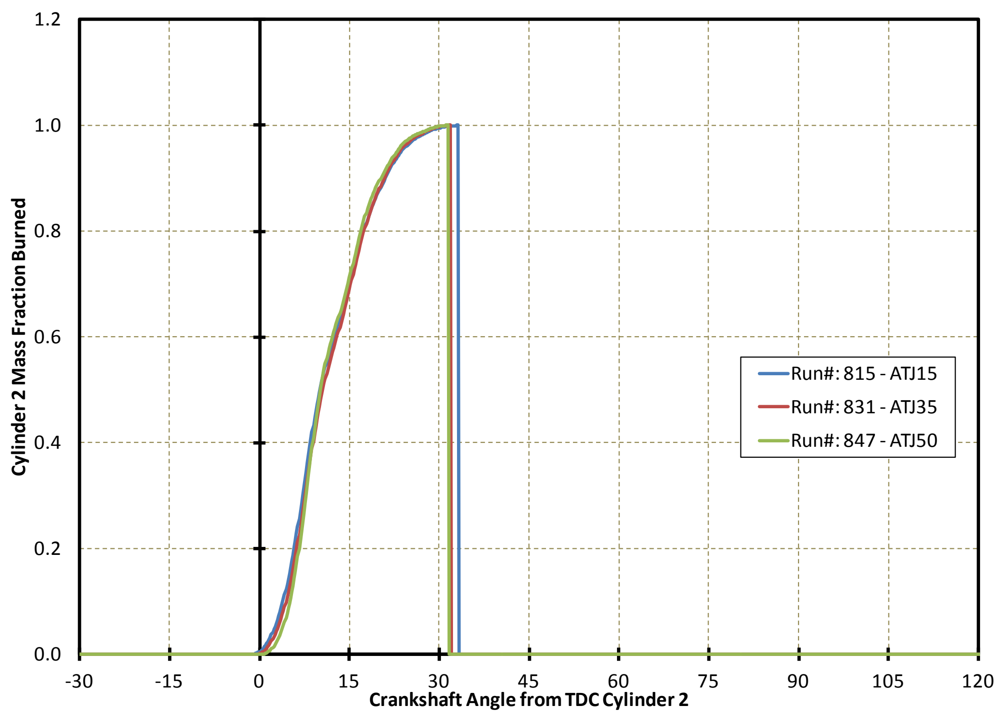


Figure A-12. Fuel Mass Fraction Burned for 2,641-RPM and 50% Load, ESC3

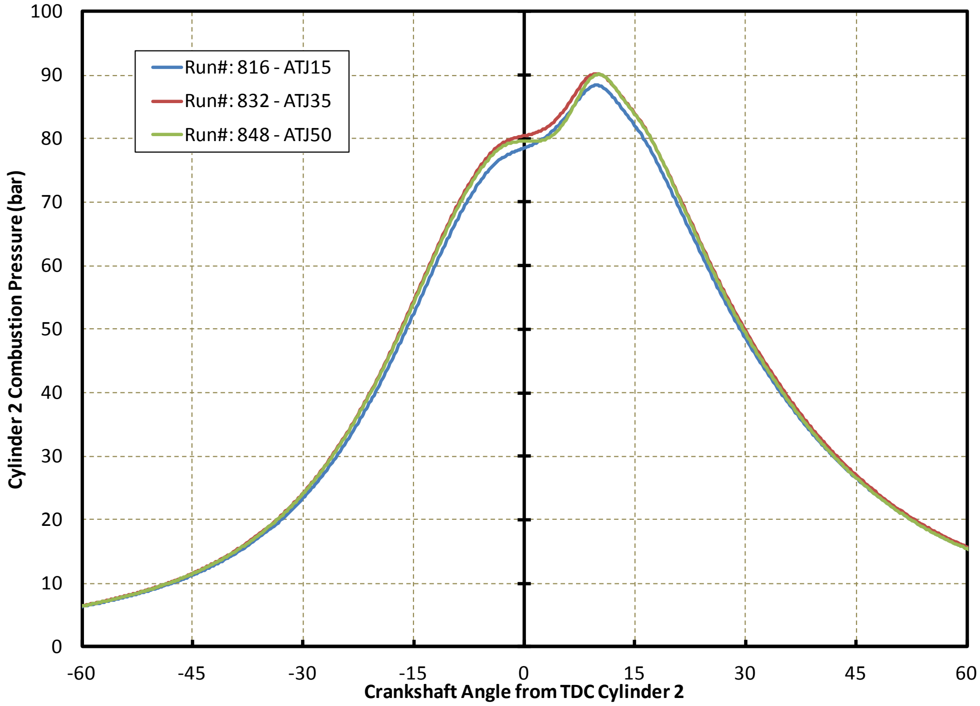
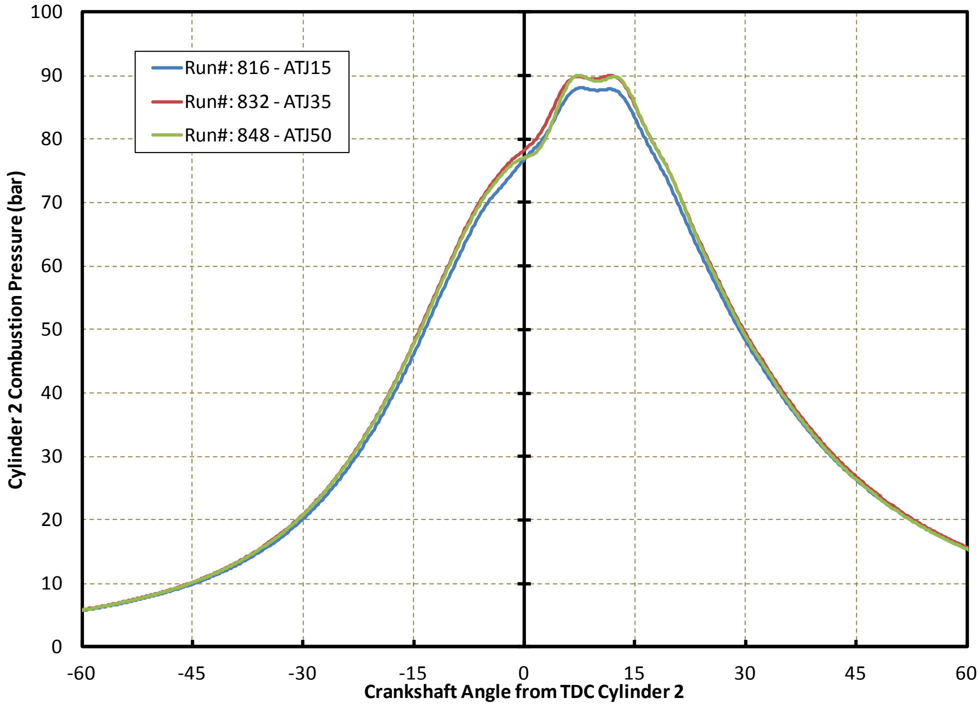


Figure A-13. Main Chamber Pressure Histories for 2,641-RPM and 75% Load, ESC4



FigureA-14. Pre-Chamber Pressure Histories for 2,641-RPM and 75% Load, ESC4

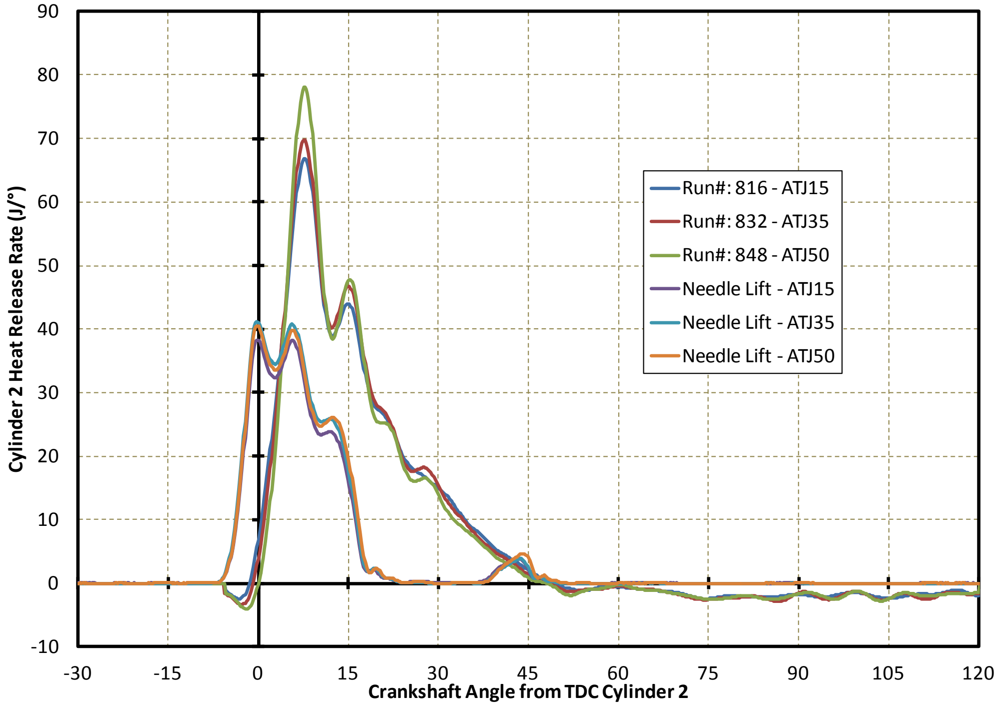


Figure A-15. Heat Release Rate Histories for 2,641-RPM and 75% Load, ESC4

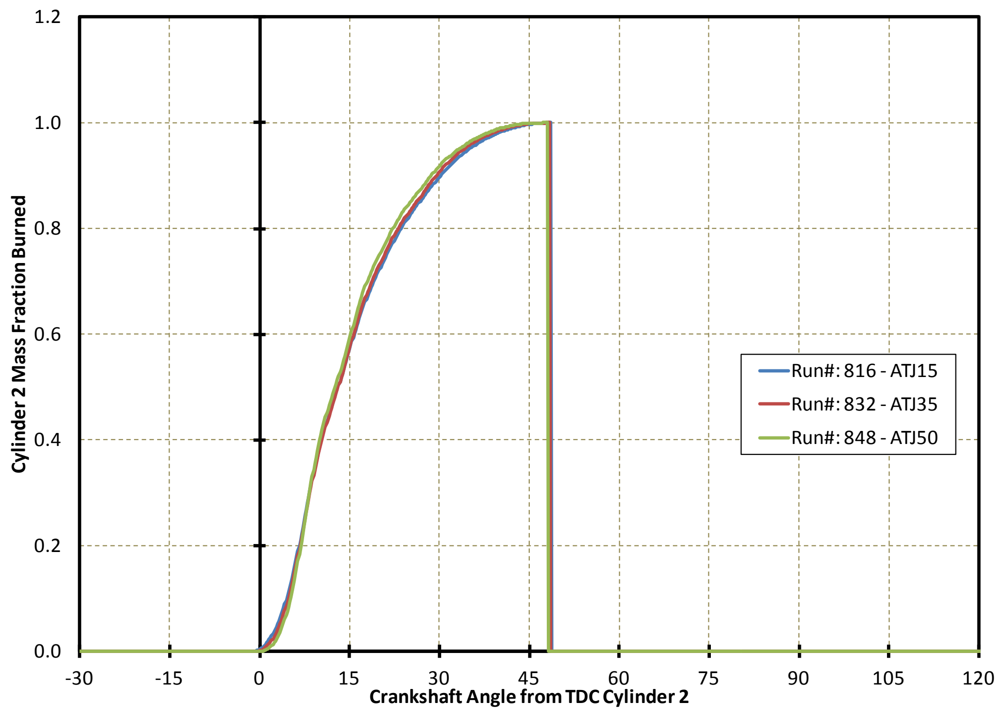


Figure A-16. Fuel Mass Fraction Burned for 2,641-RPM and 75% Load, ESC4

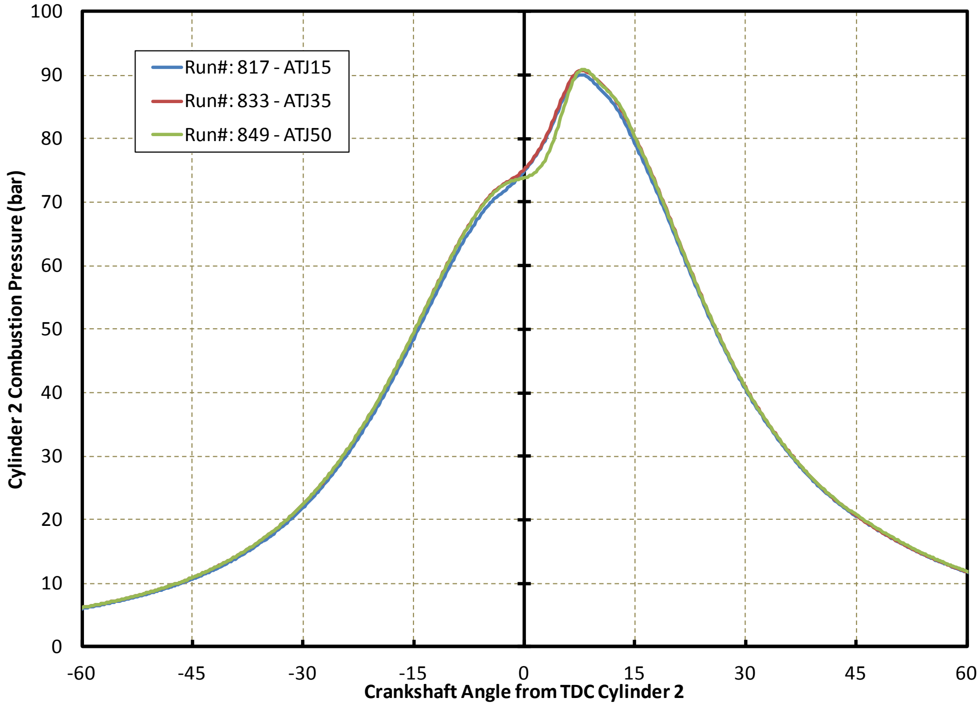


Figure A-17. Main Chamber Pressure Histories for 1,928-RPM and 50% Load, ESC5

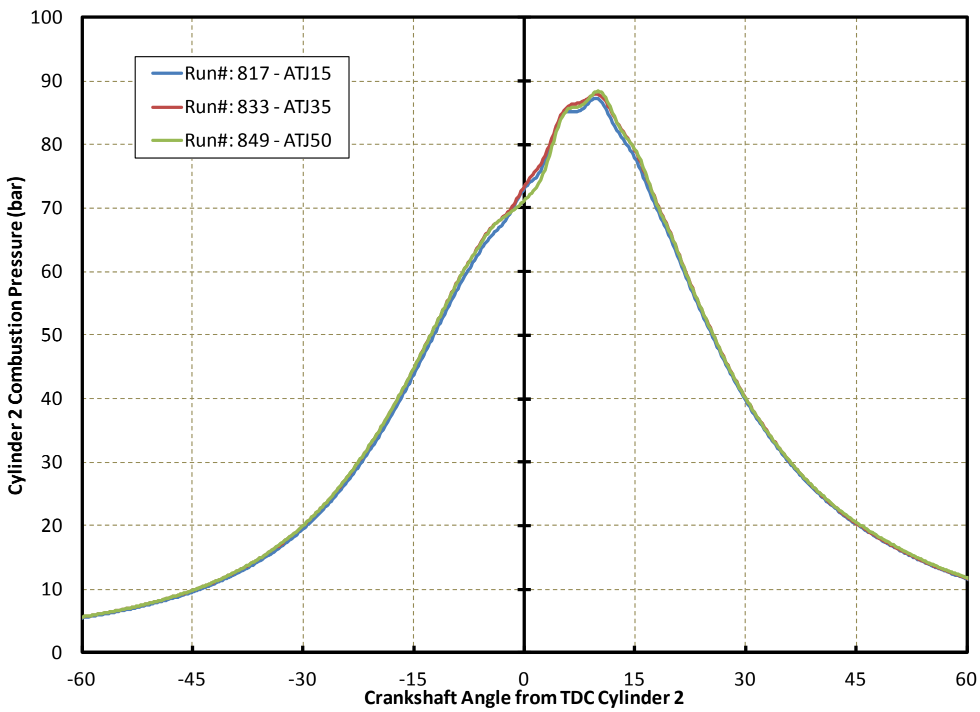


Figure A-18. Pre-Chamber Pressure Histories for 1,928-RPM and 50% Load, ESC5

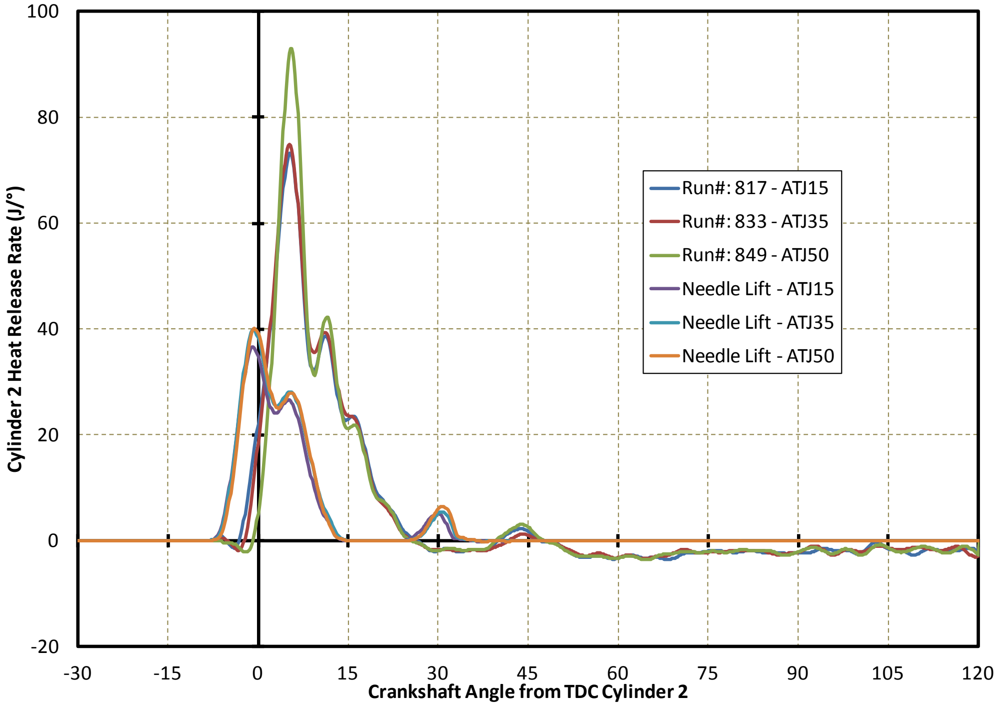


Figure A-19. Heat Release Rate Histories for 1,928-RPM and 50% Load, ESC5

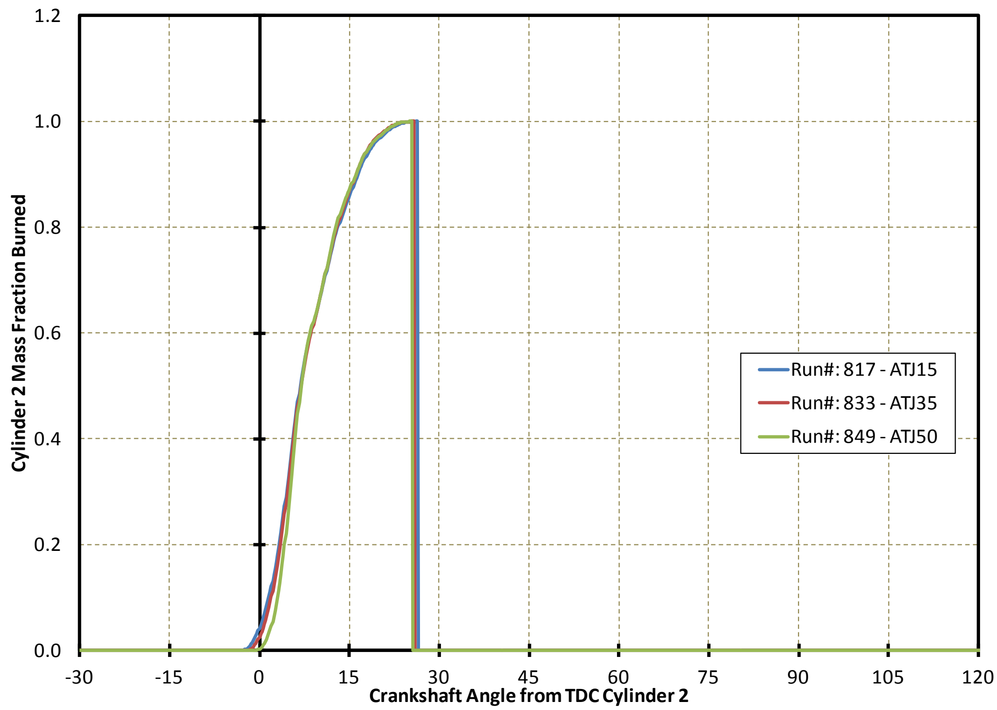


Figure A-20. Fuel Mass Fraction Burned for 1,928-RPM and 50% Load, ESC5

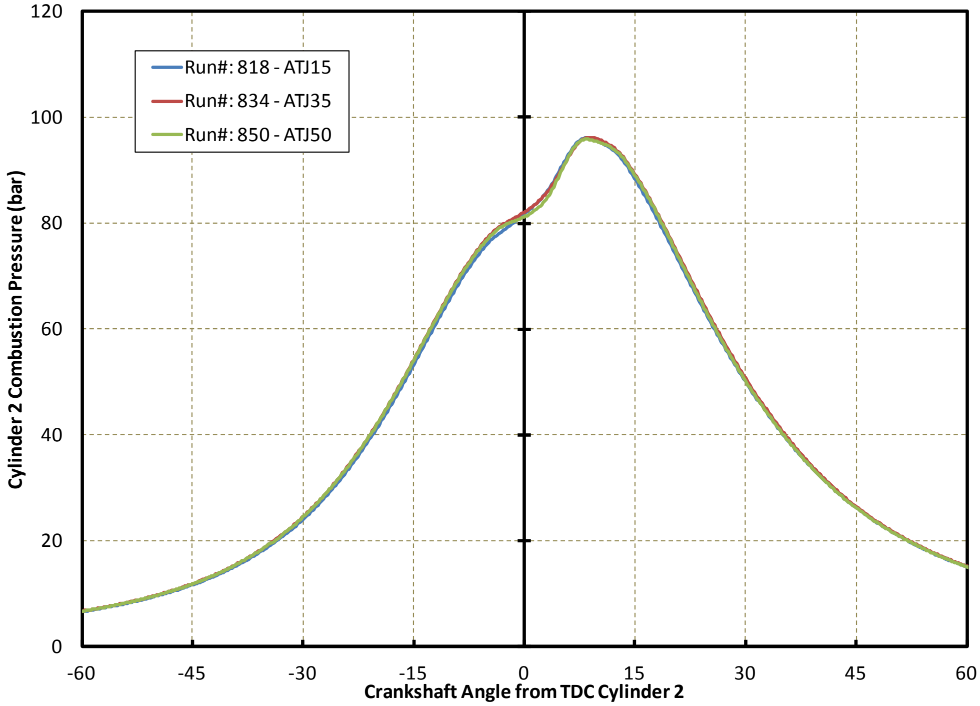


Figure A-21. Main Chamber Pressure Histories for 1,928-RPM and 75% Load, ESC6

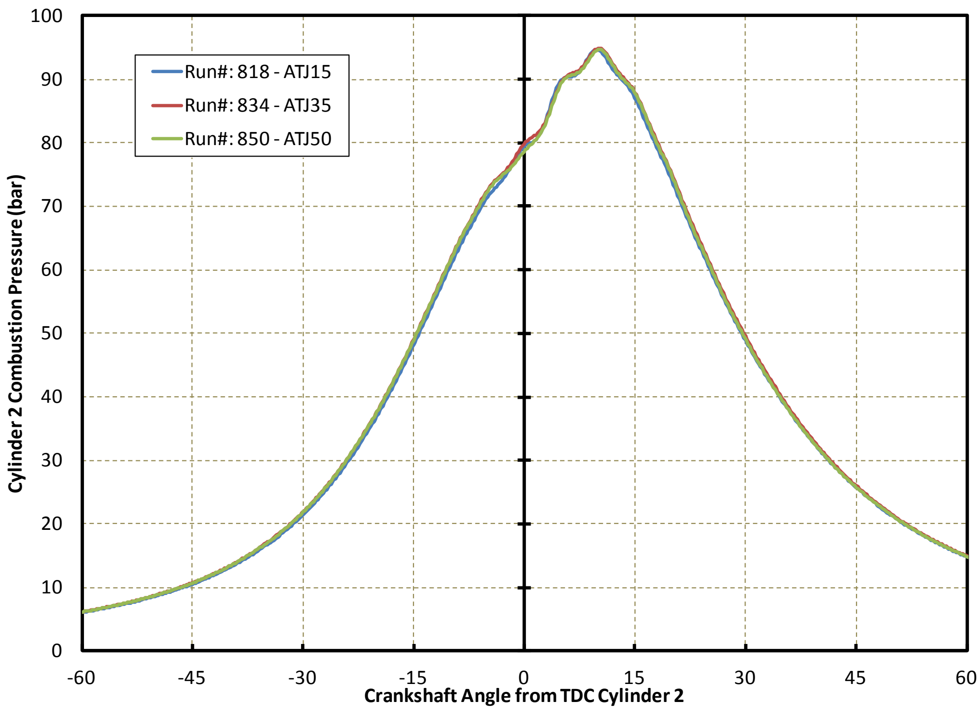


Figure A-22. Pre-Chamber Pressure Histories for 1,928-RPM and 75% Load, ESC6

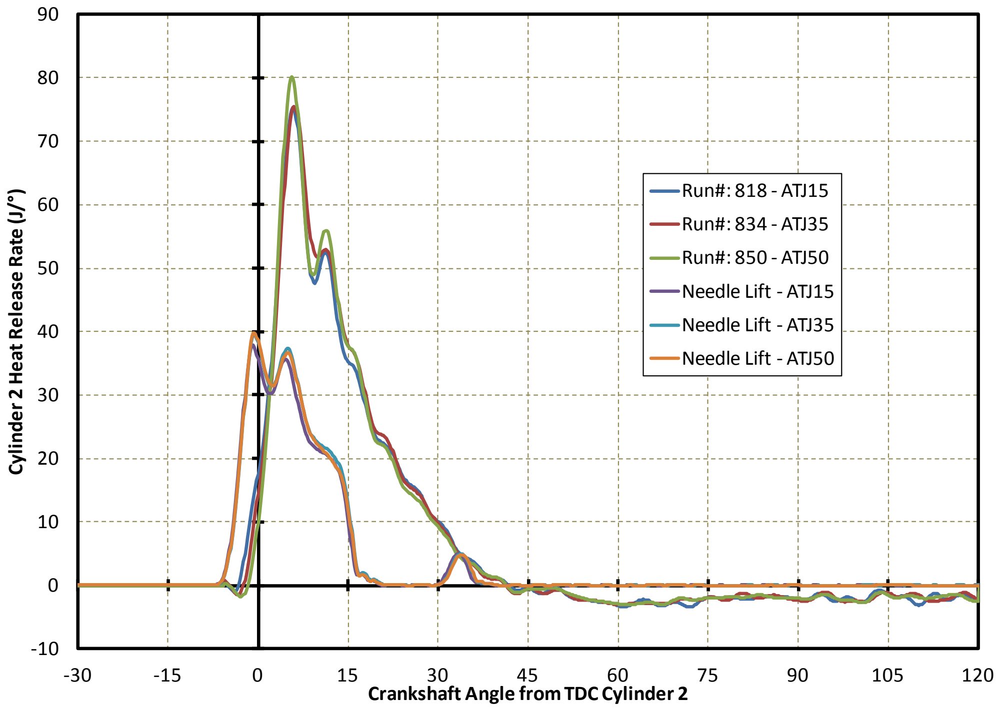


Figure A-23. Heat Release Rate Histories for 1,928-RPM and 75% Load, ESC6

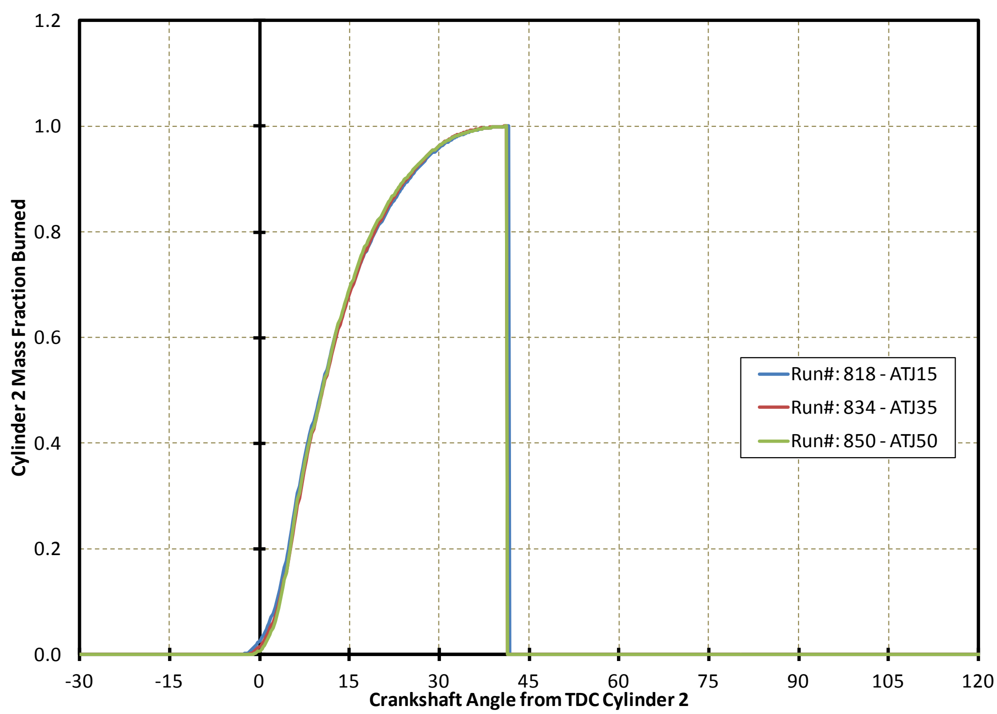


Figure A-24. Fuel Mass Fraction Burned for 1,928-RPM and 75% Load, ESC6

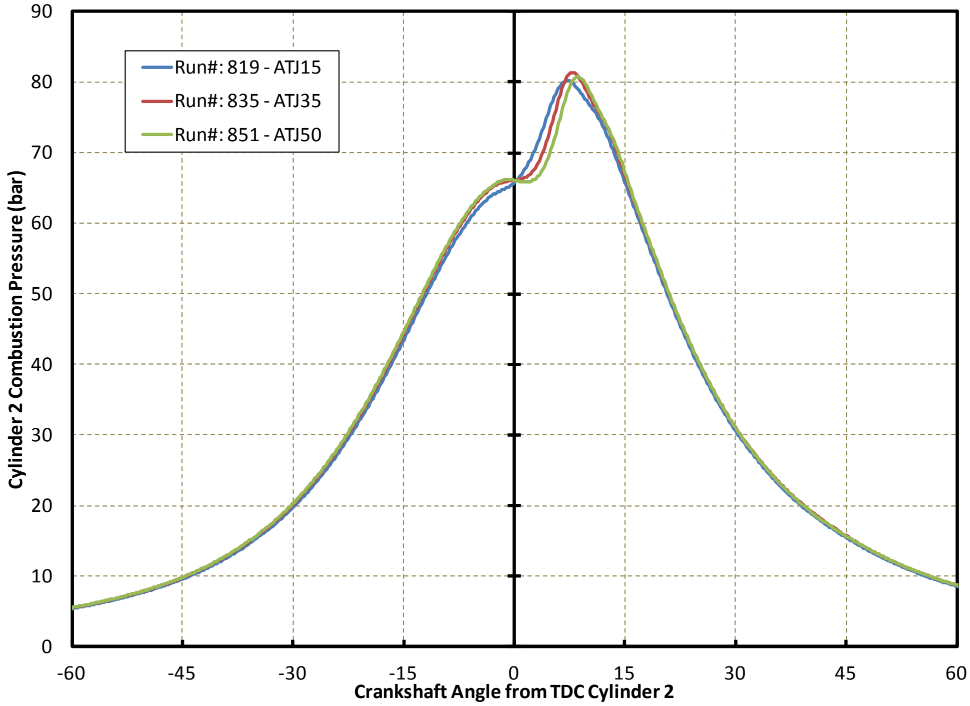


Figure A-25. Main Chamber Pressure Histories for 1,928-RPM and 25% Load, ESC7

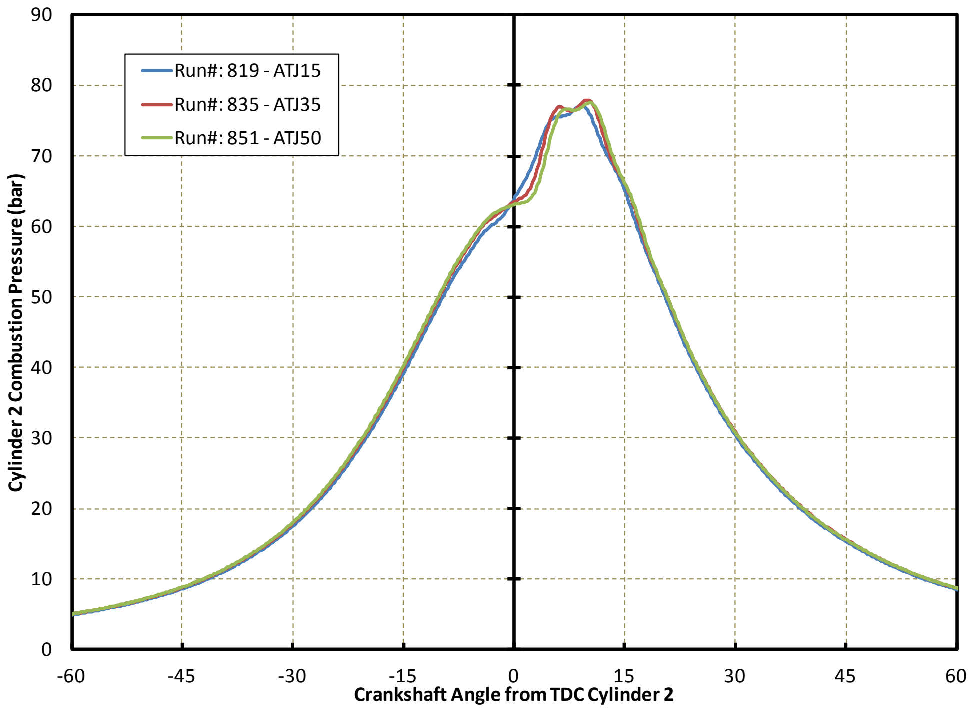


Figure A-26. Pre-Chamber Pressure Histories for 1,928-RPM and 25% Load, ESC7

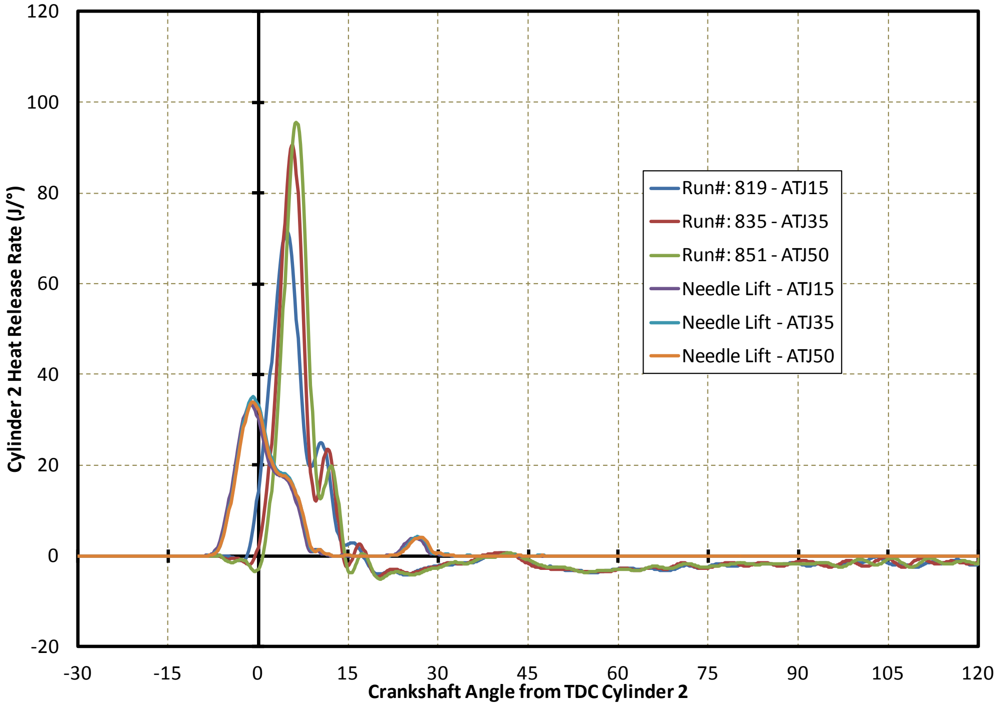


Figure A-27. Heat Release Rate Histories for 1,928-RPM and 25% Load, ESC7

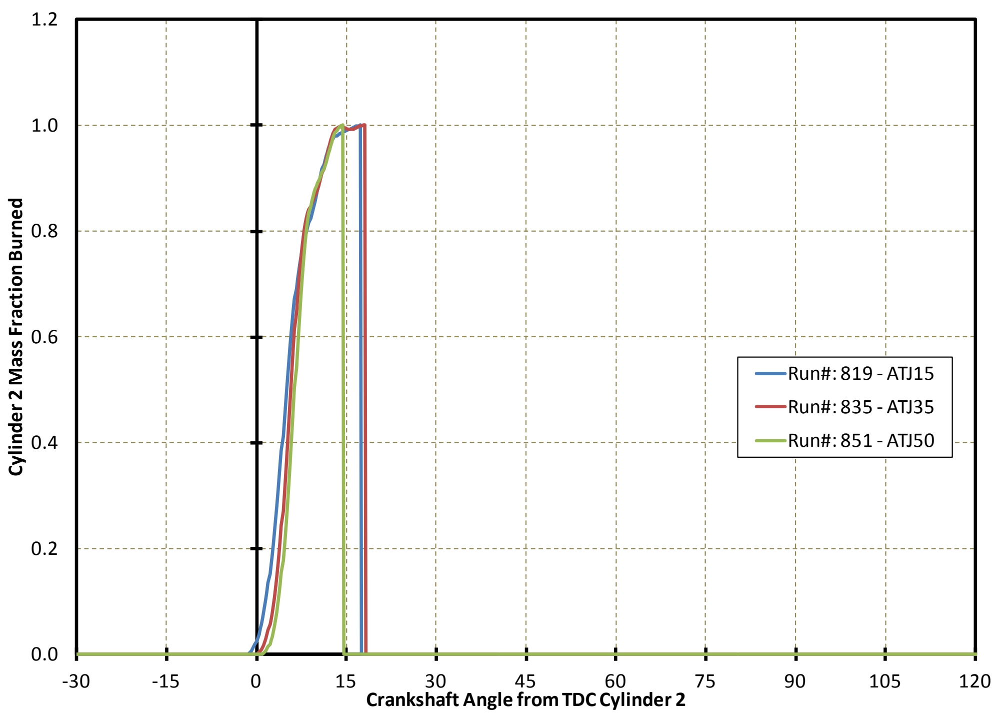


Figure A-28. Fuel Mass Fraction Burned for 1,928-RPM and 25% Load, ESC7

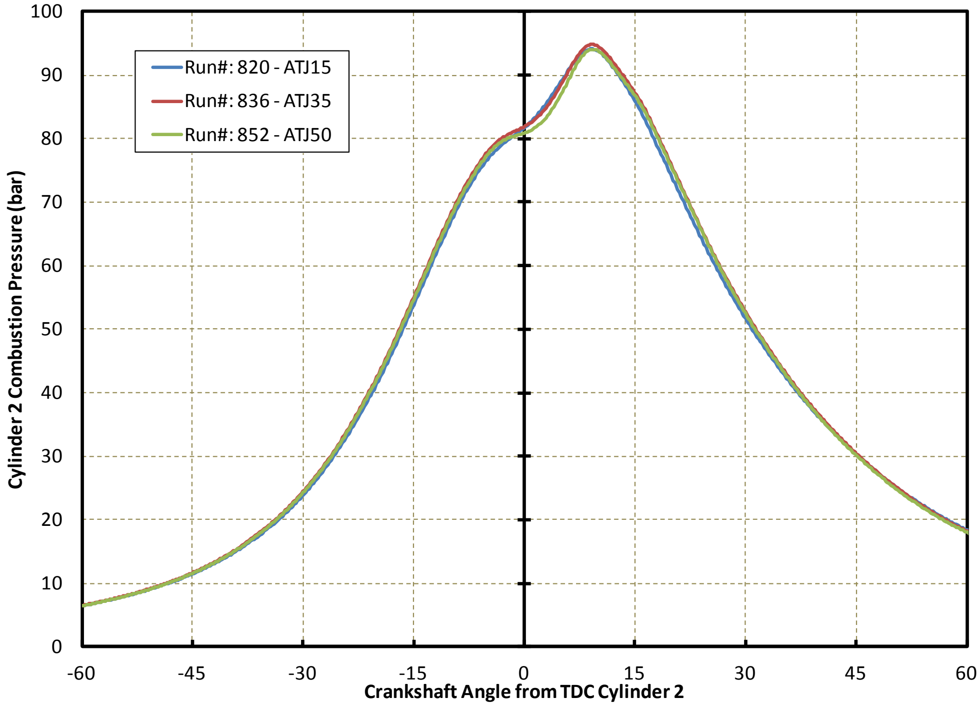


Figure A-29. Main Chamber Pressure Histories for 2,641-RPM and 100% Load, ESC8

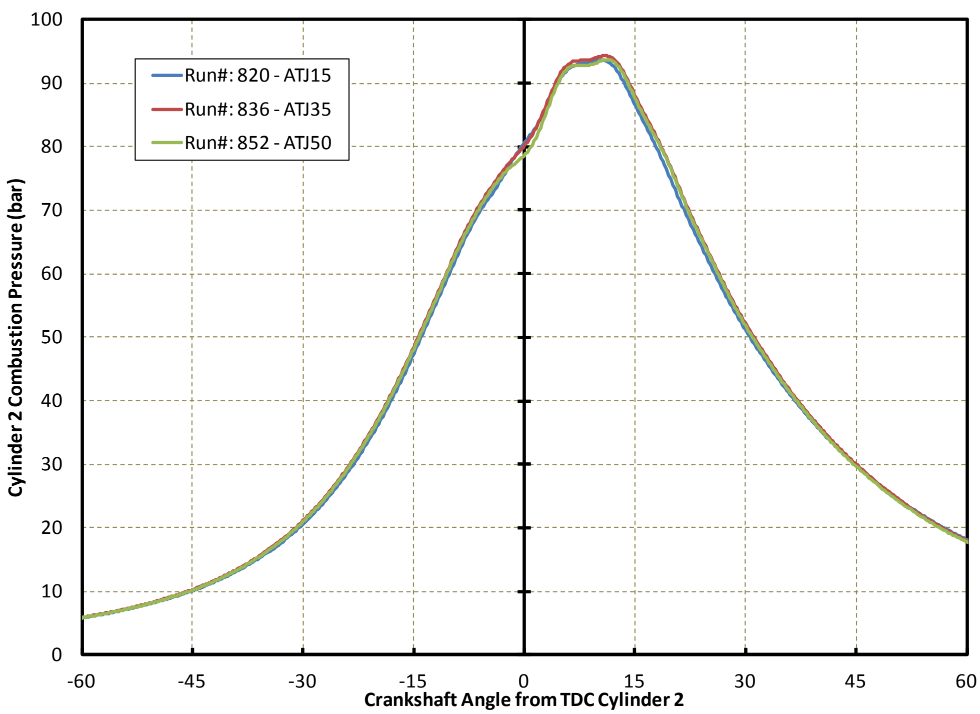


Figure A-30. Pre-Chamber Pressure Histories for 2,641-RPM and 100% Load, ESC8

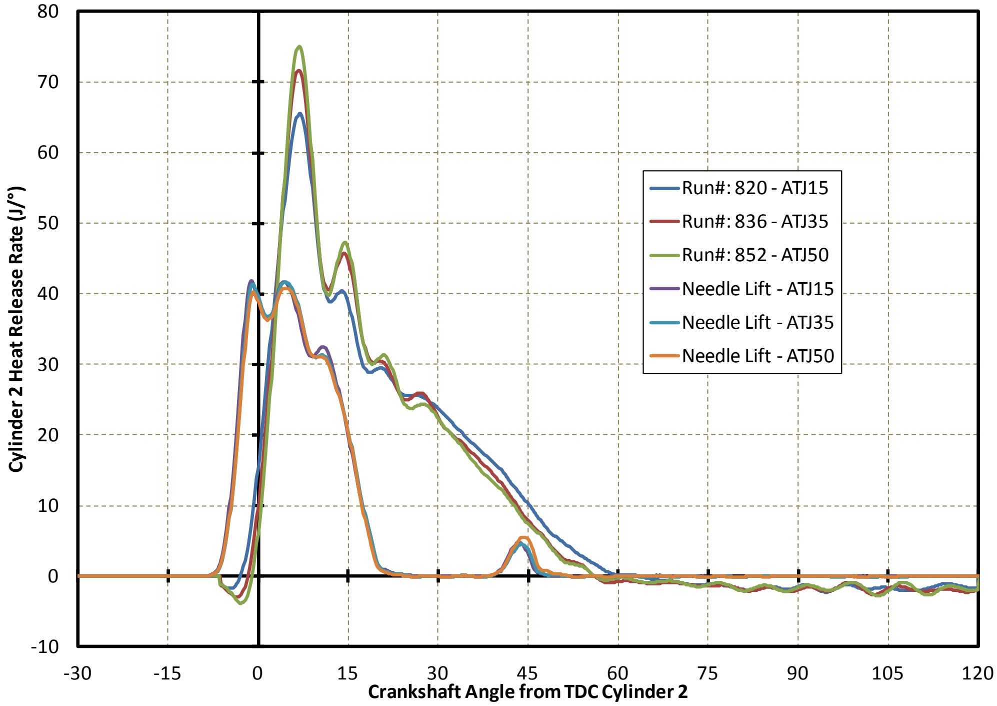


Figure A-31. Heat Release Rate Histories for 2,641-RPM and 100% Load, ESC8

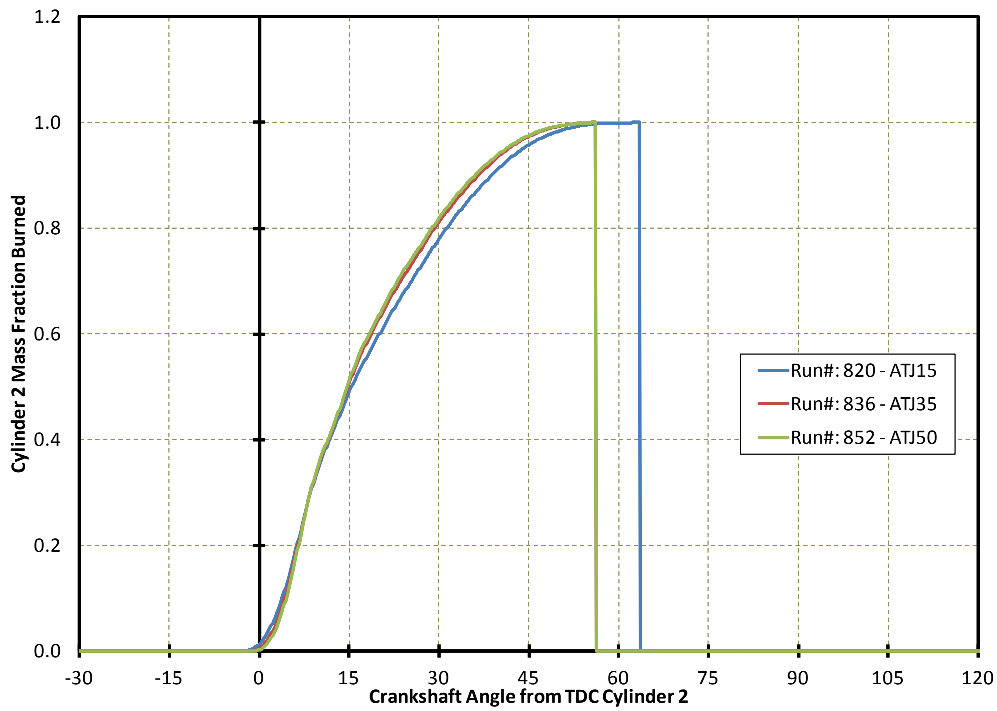


Figure A-32. Fuel Mass Fraction Burned for 2,641-RPM and 100% Load, ESC8

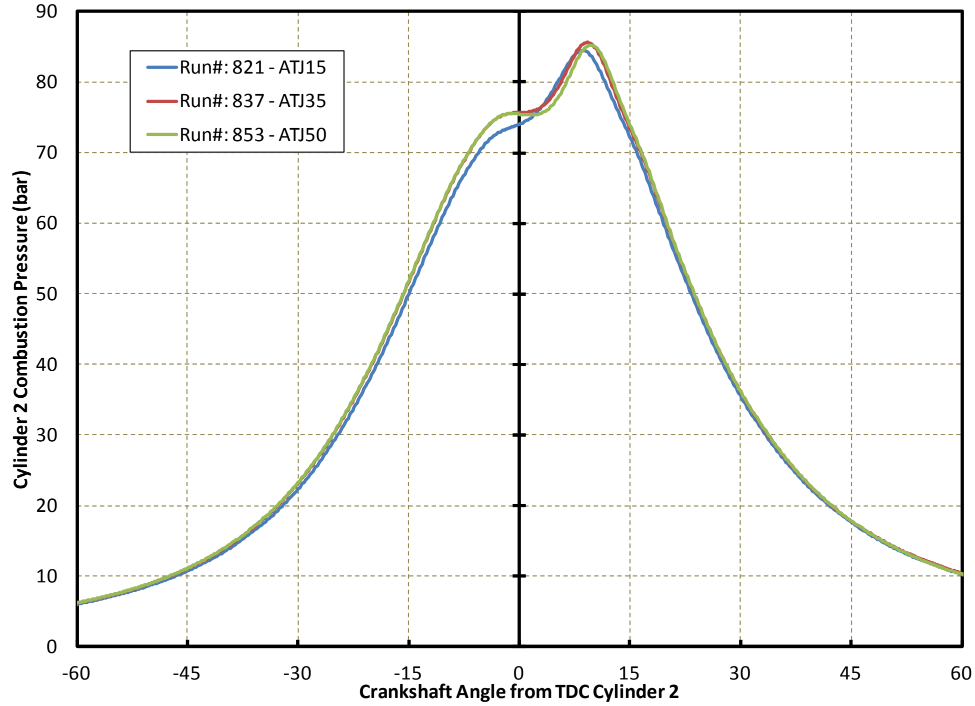


Figure A-33. Main Chamber Pressure Histories for 2,641-RPM and 25% Load, ESC9

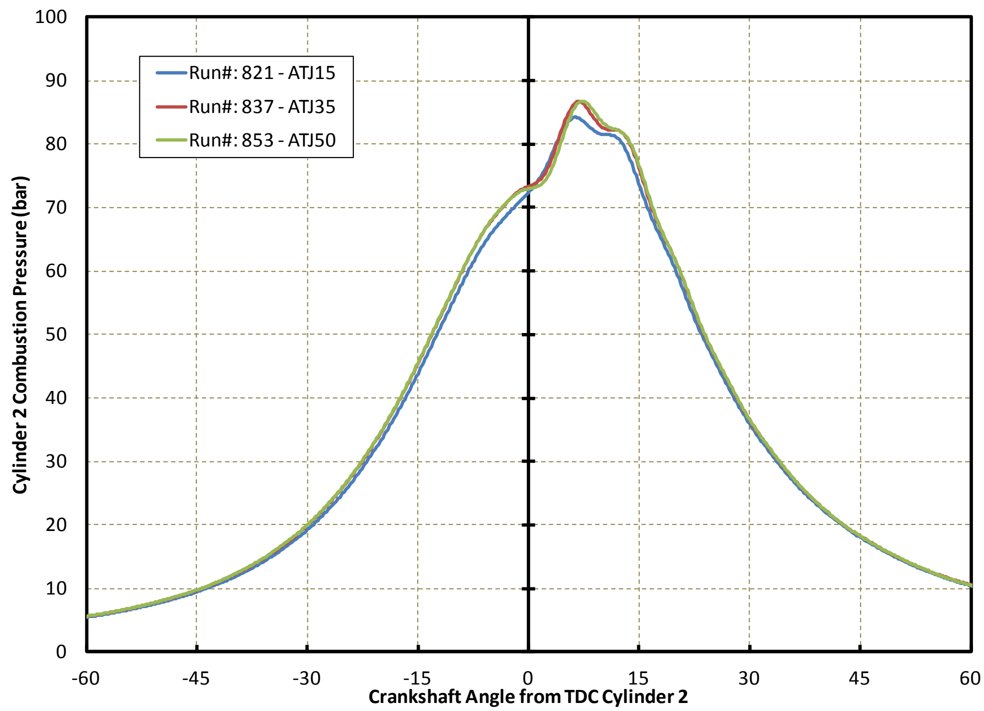


Figure A-34. Pre-Chamber Pressure Histories for 2,641-RPM and 25% Load, ESC9

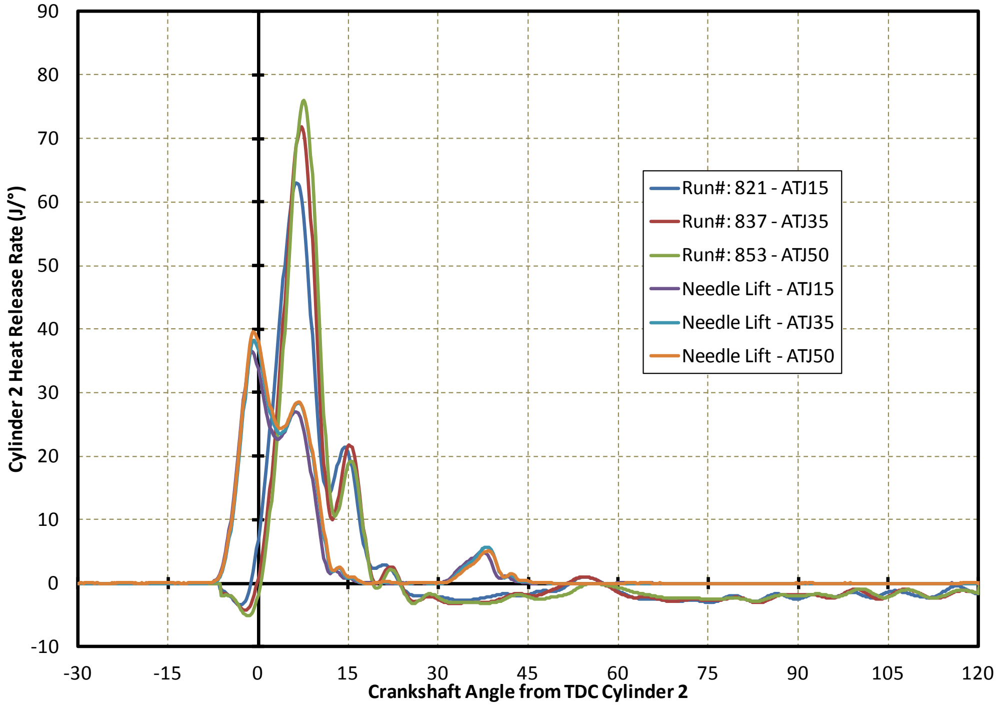


Figure A-35. Heat Release Rate Histories for 2,641-RPM and 25% Load, ESC9

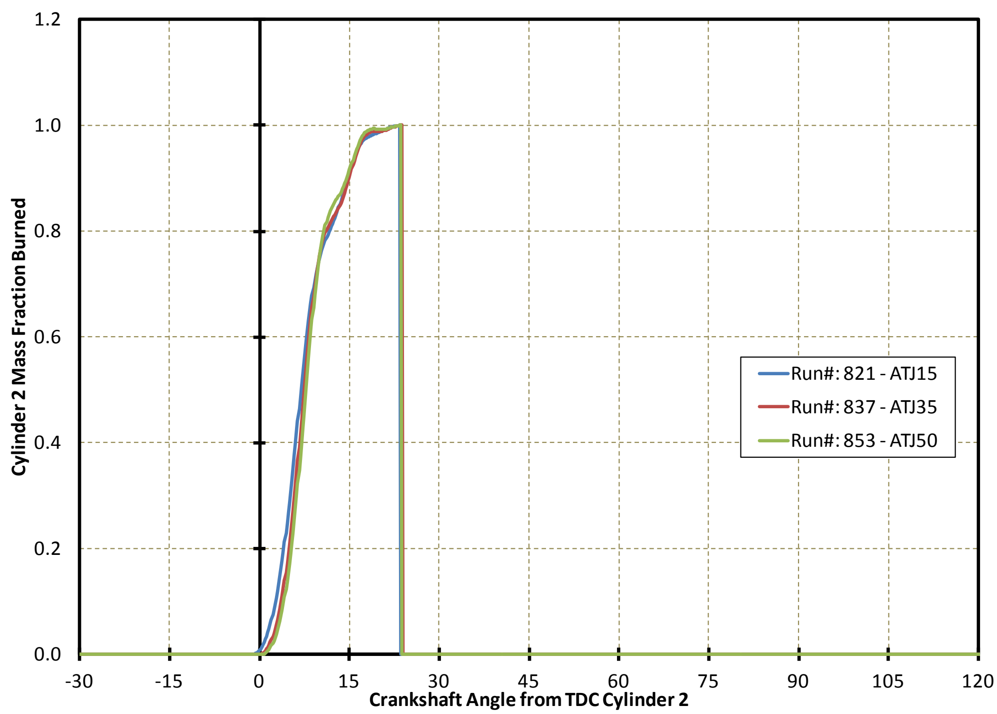


Figure A-36. Fuel Mass Fraction Burned for 2,641-RPM and 25% Load, ESC9

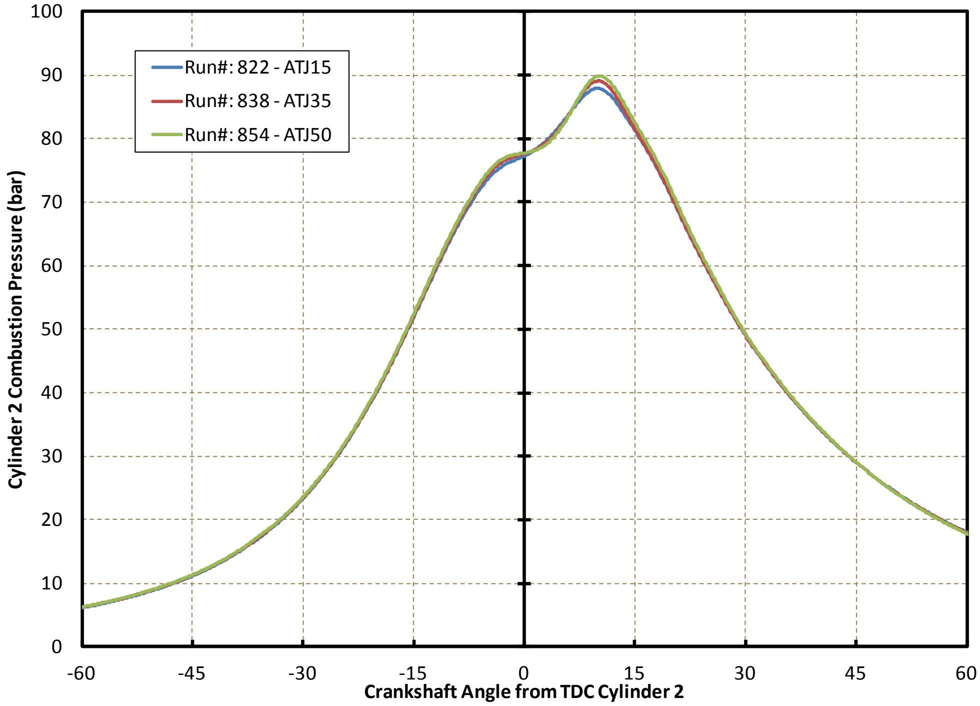


Figure A-37. Main Chamber Pressure Histories for 2,995-RPM and 100% Load, ESC10

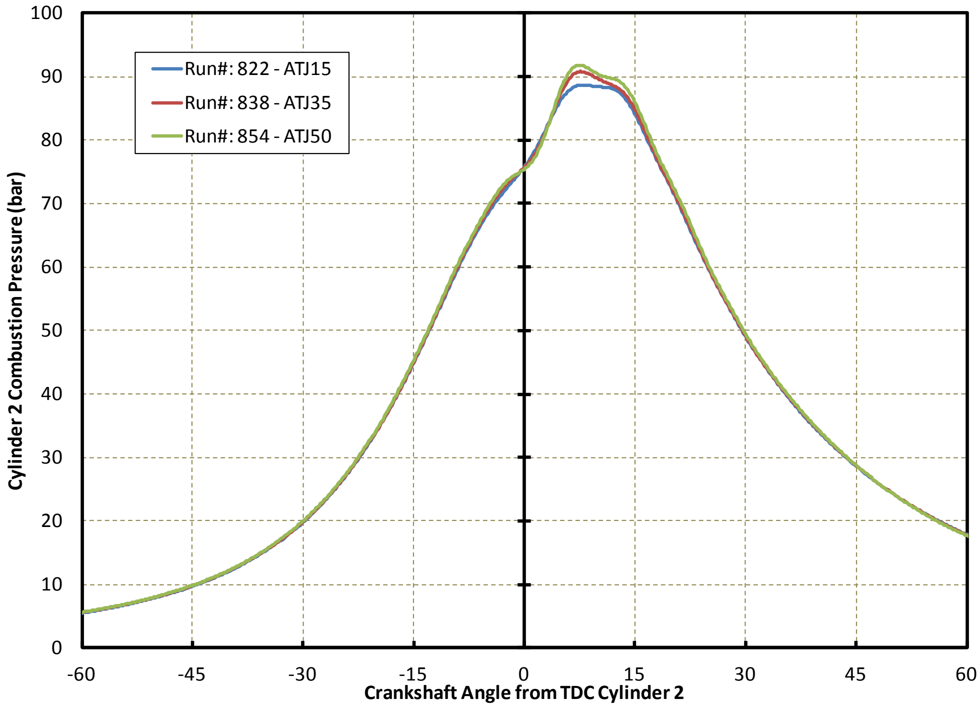


Figure A-38. Pre-Chamber Pressure Histories for 2,995-RPM and 100% Load, ESC10

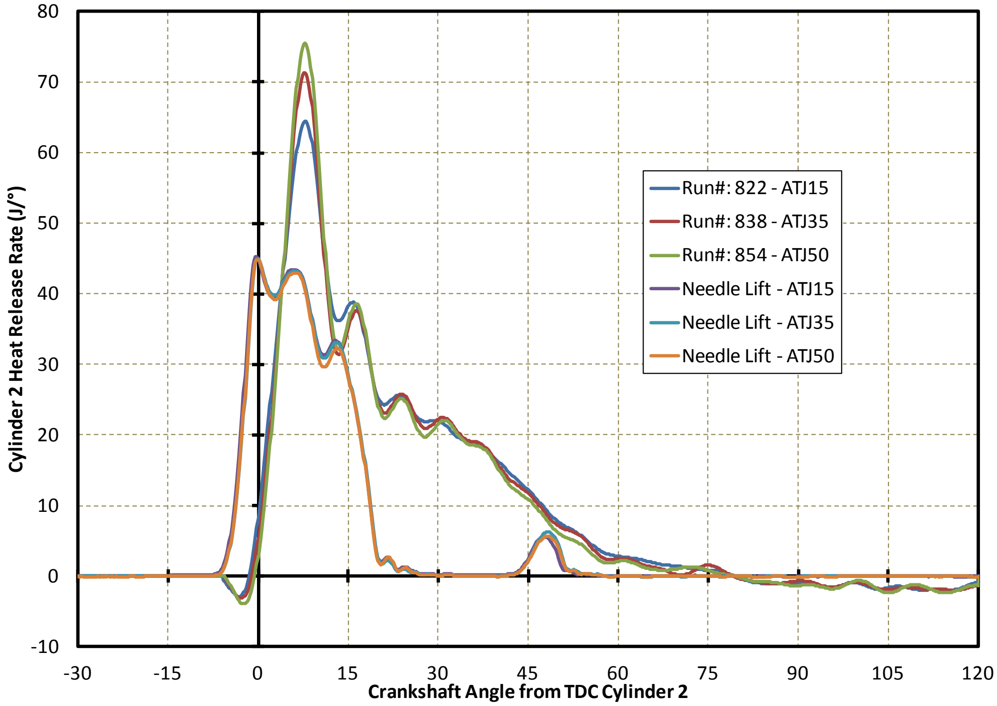


Figure A-39. Heat Release Rate Histories for 2,995-RPM and 100% Load, ESC10

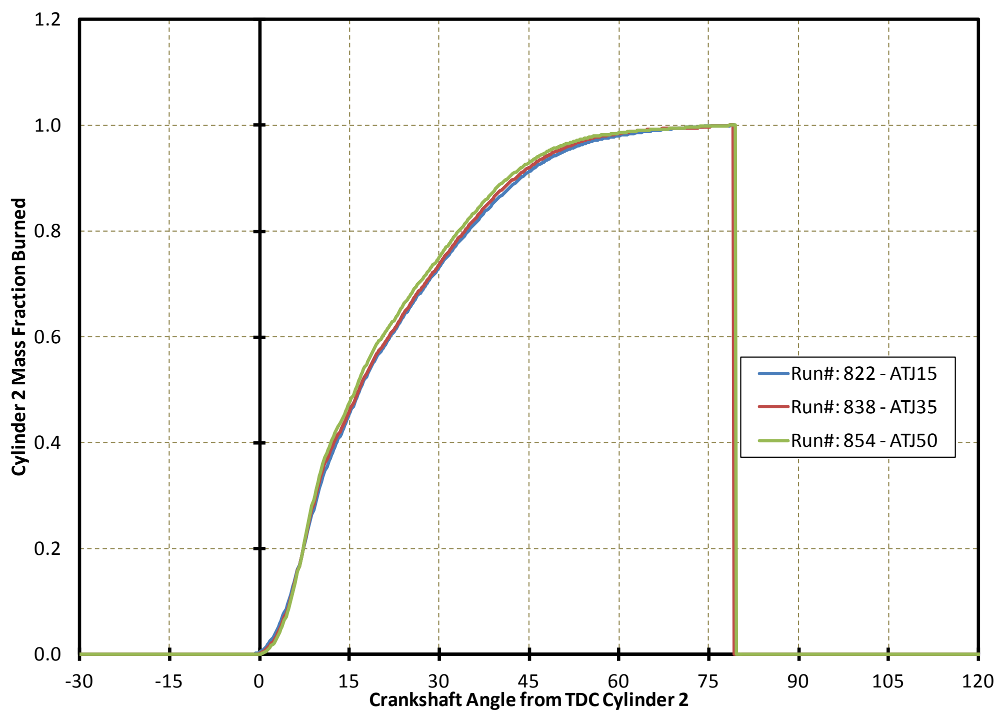


Figure A-40. Fuel Mass Fraction Burned for 2,995-RPM and 100% Load, ESC10

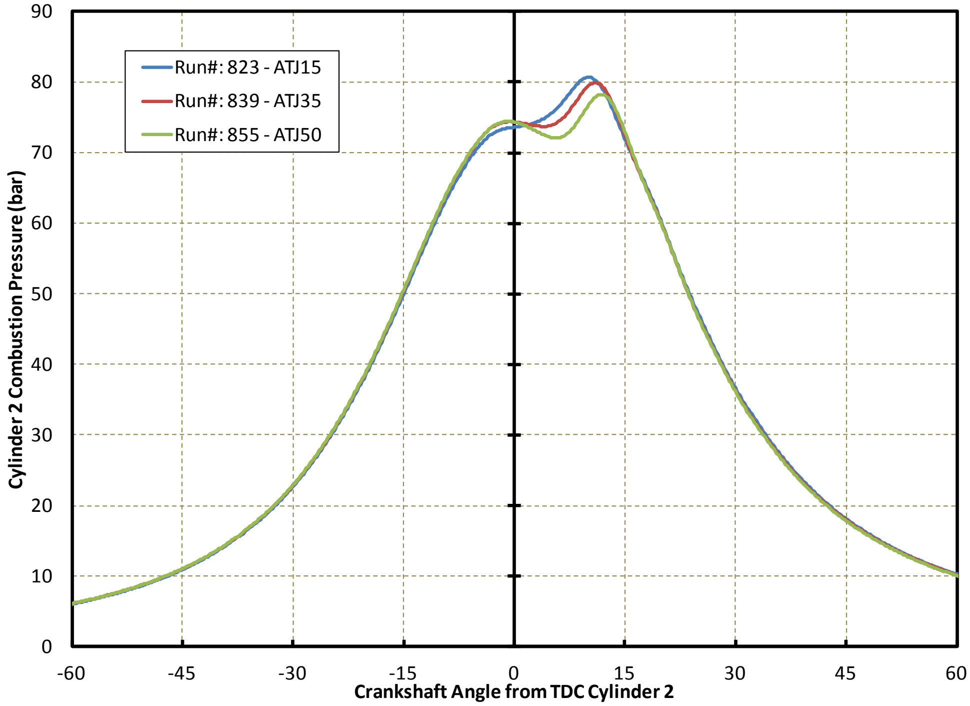


Figure A-41. Main Chamber Pressure Histories for 2,995-RPM and 25% Load, ESC11

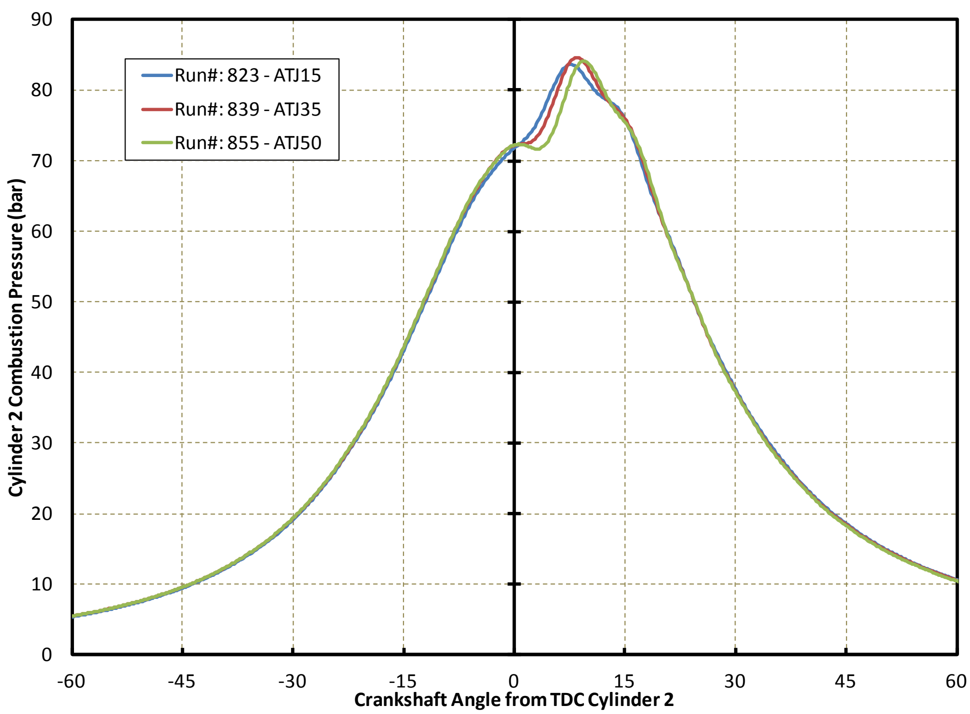


Figure A-42. Pre-Chamber Pressure Histories for 2,995-RPM and 25% Load, ESC11

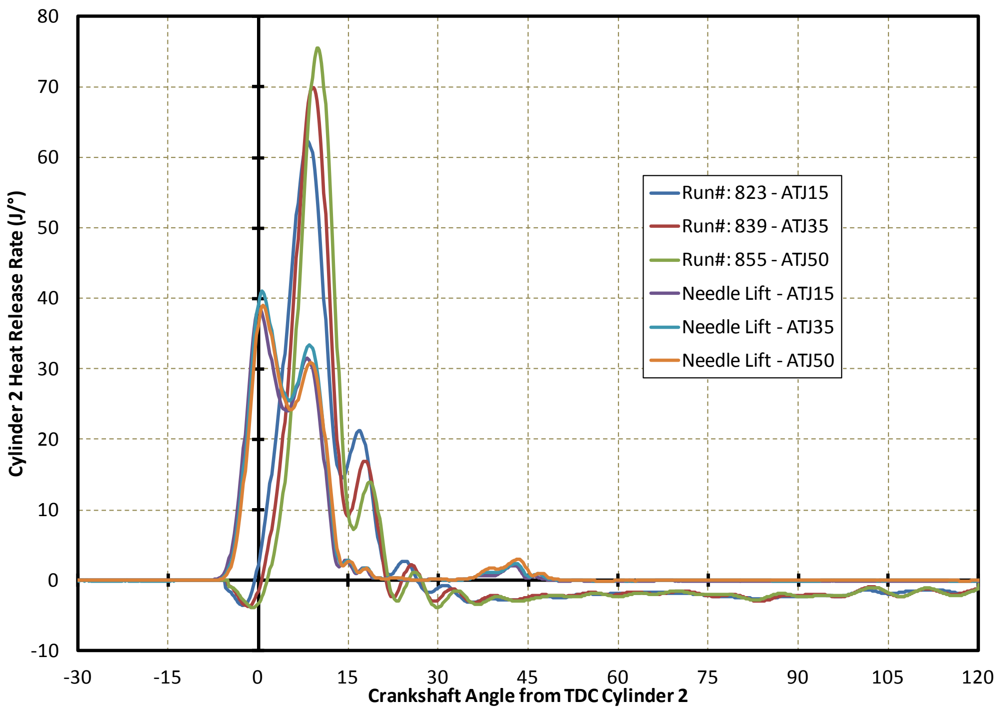


Figure A-43. **Heat Release Rate Histories for 2,995-RPM and 25% Load, ESC11**

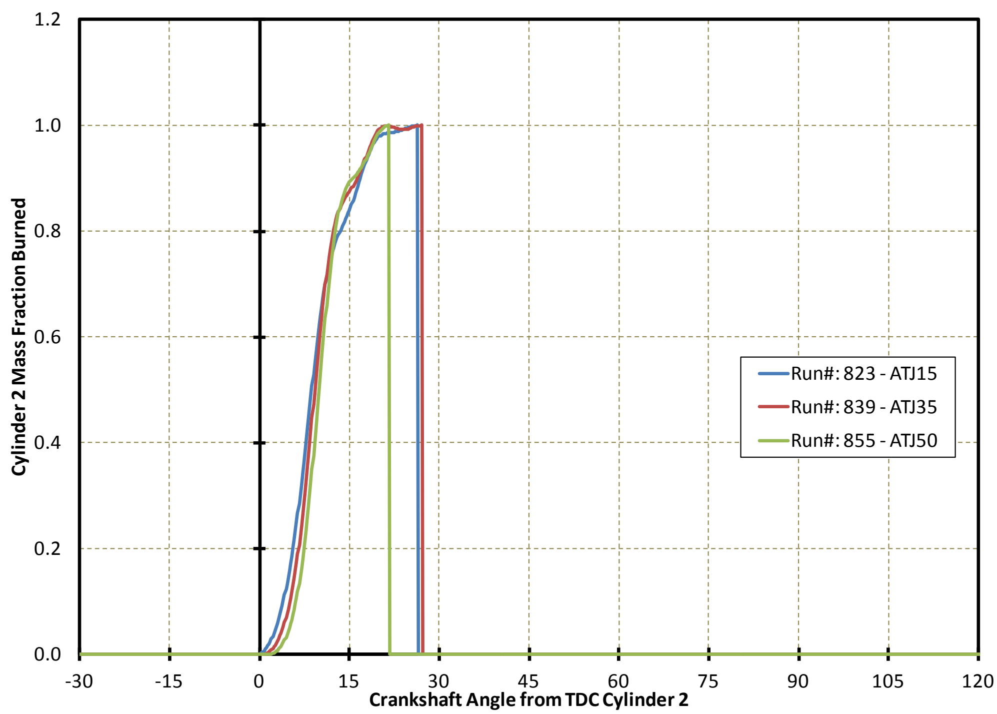


Figure A-44. **Fuel Mass Fraction Burned for 2,995-RPM and 25% Load, ESC11**

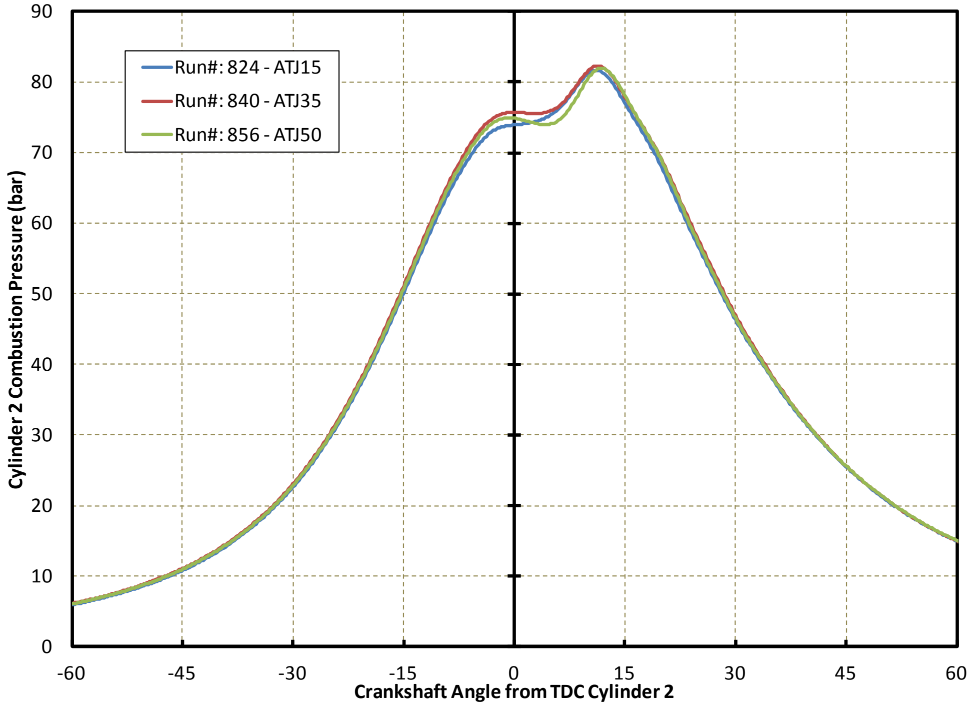


Figure A-45. Main Chamber Pressure Histories for 2,995-RPM and 75% Load, ESC12

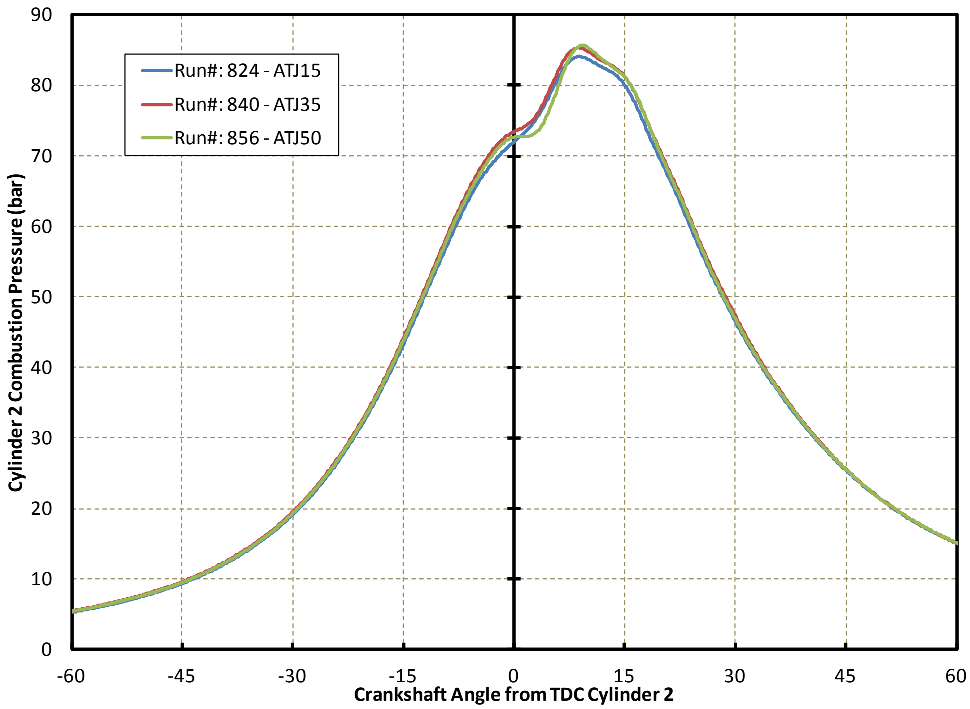


Figure A-46. Pre-Chamber Pressure Histories for 2,995-RPM and 75% Load, ESC12

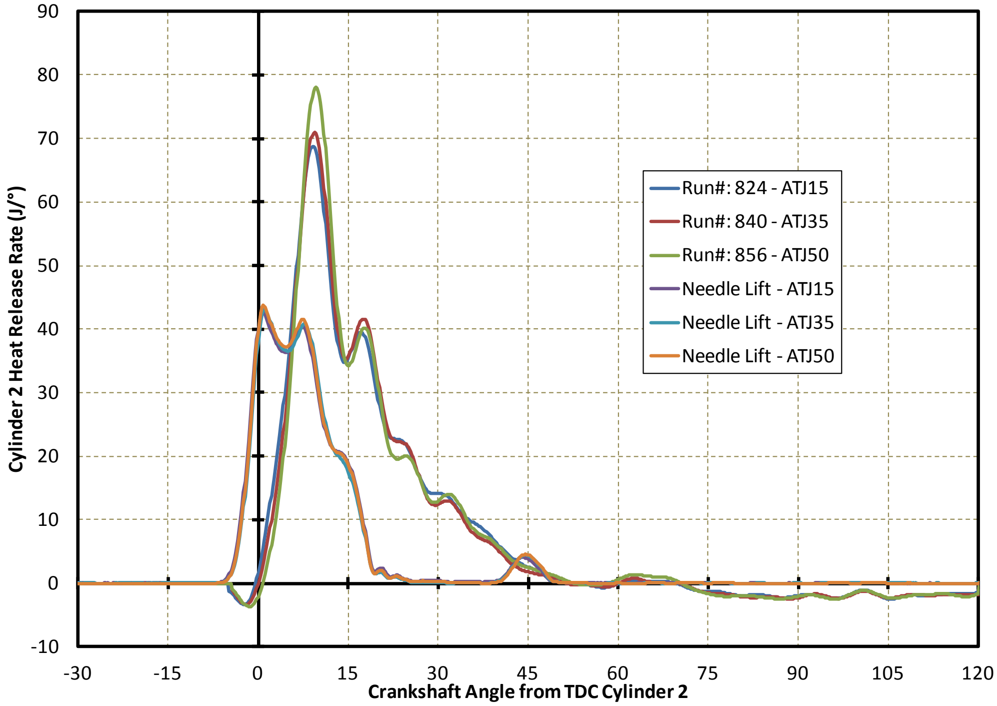


Figure A-47. Heat Release Rate Histories for 2,995-RPM and 75% Load, ESC12

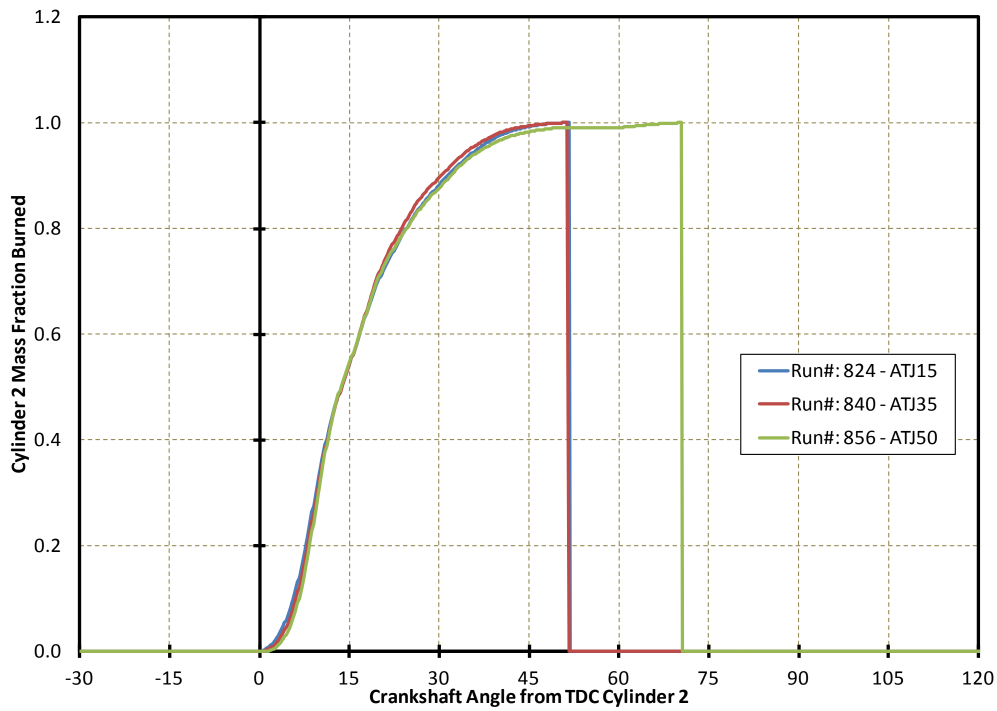


Figure A-48. Fuel Mass Fraction Burned for 2,995-RPM and 75% Load, ESC12

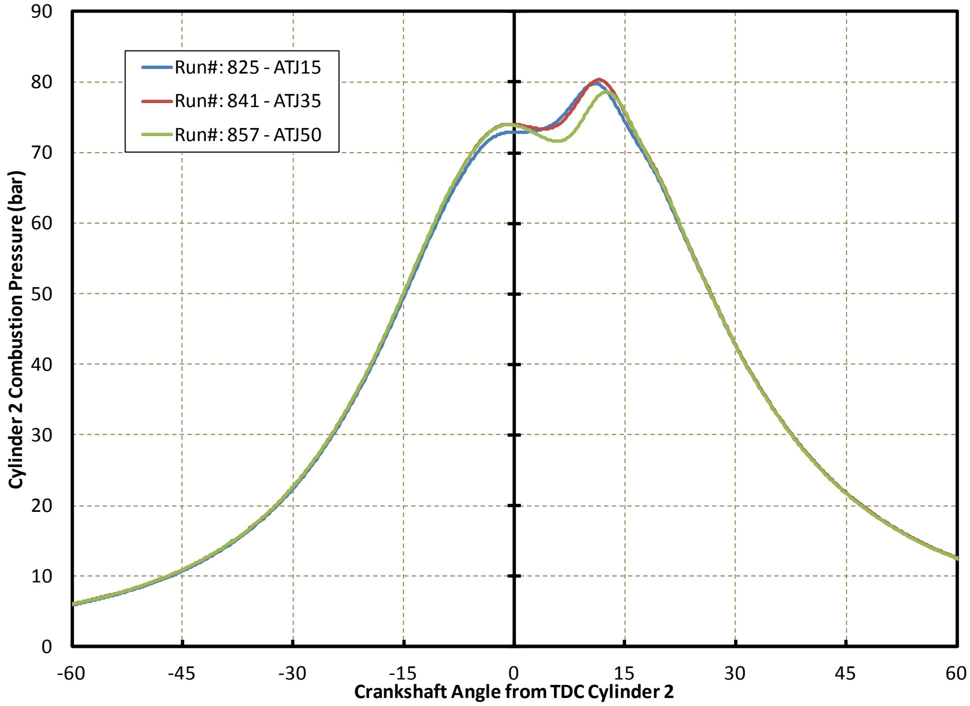


Figure A-49. Main Chamber Pressure Histories for 2,995-RPM and 50% Load, ESC13

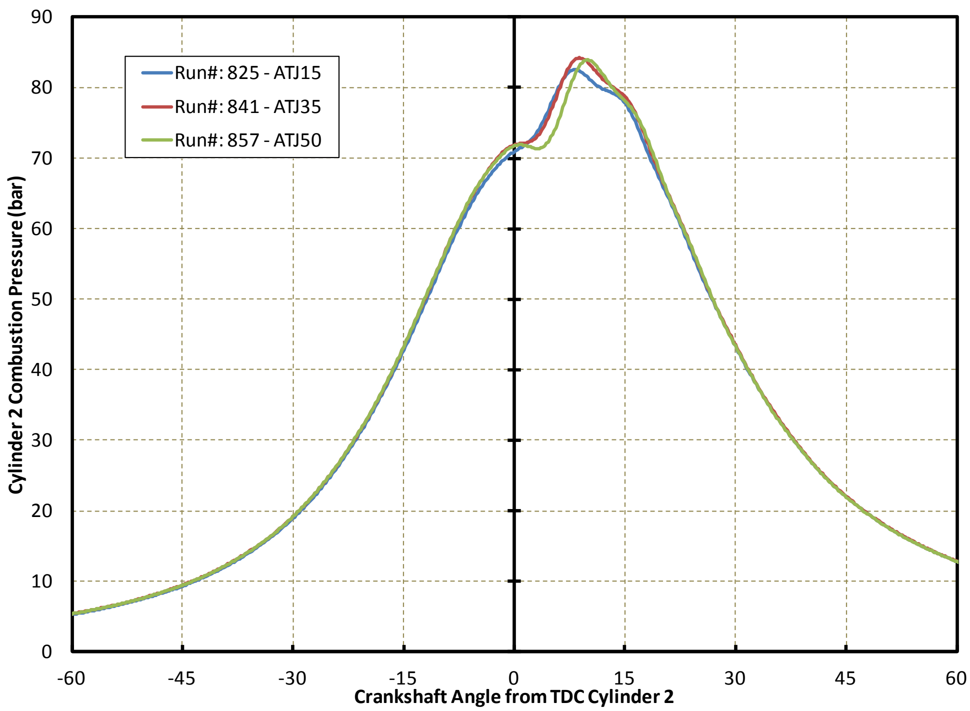


Figure A-50. Pre-Chamber Pressure Histories for 2,995-RPM and 50% Load, ESC13

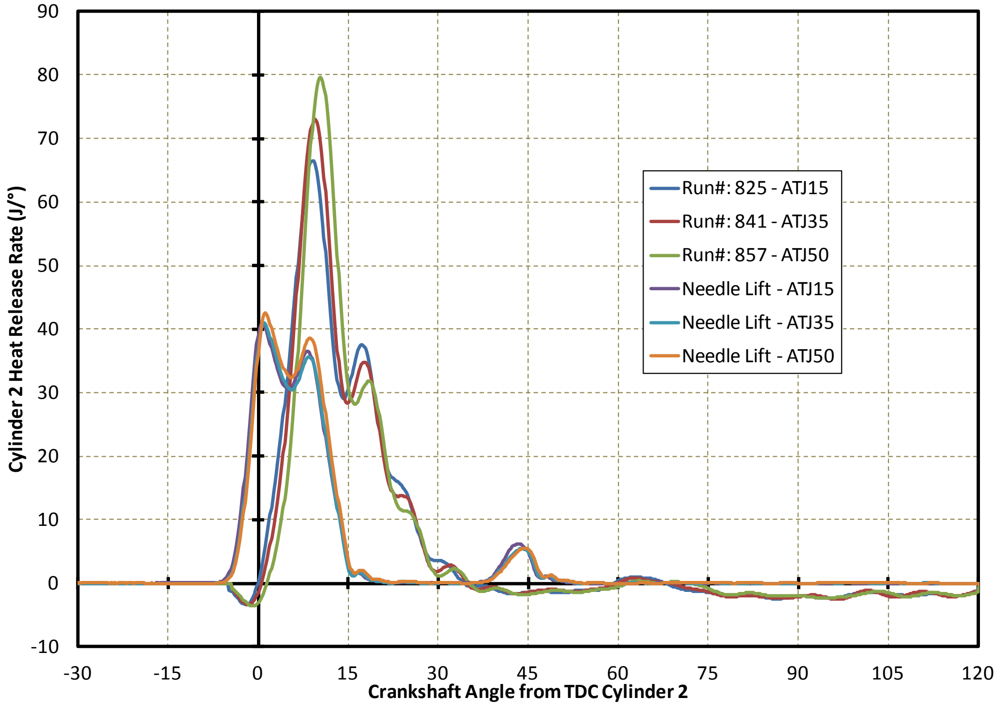


Figure A-51. Heat Release Rate Histories for 2,995-RPM and 50% Load, ESC13

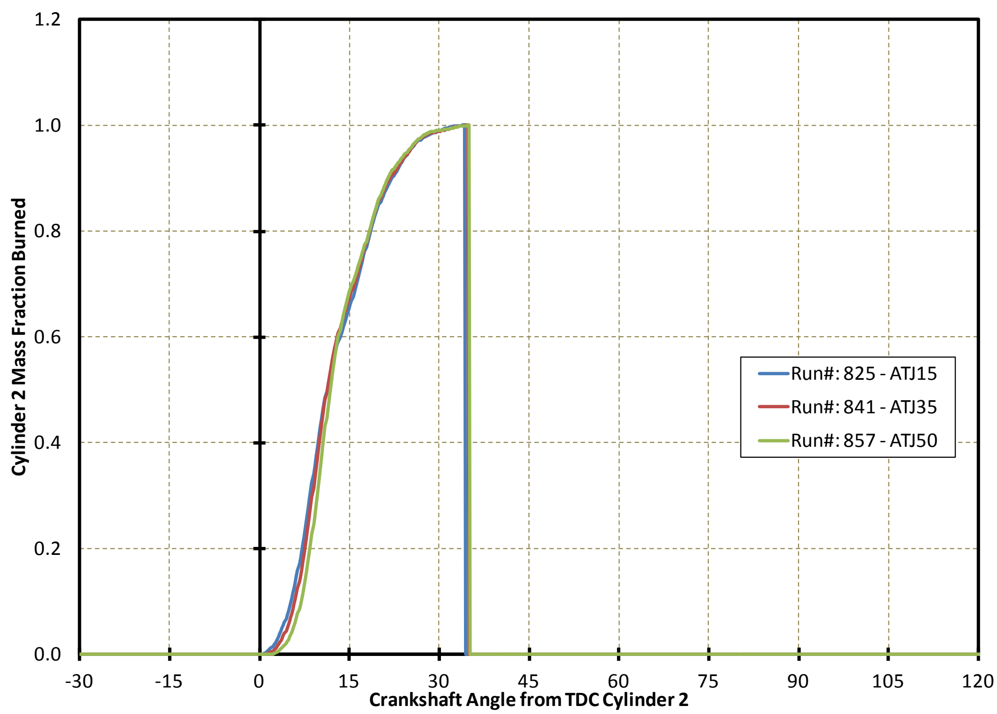


Figure A-52. Fuel Mass Fraction Burned for 2,995-RPM and 50% Load, ESC13